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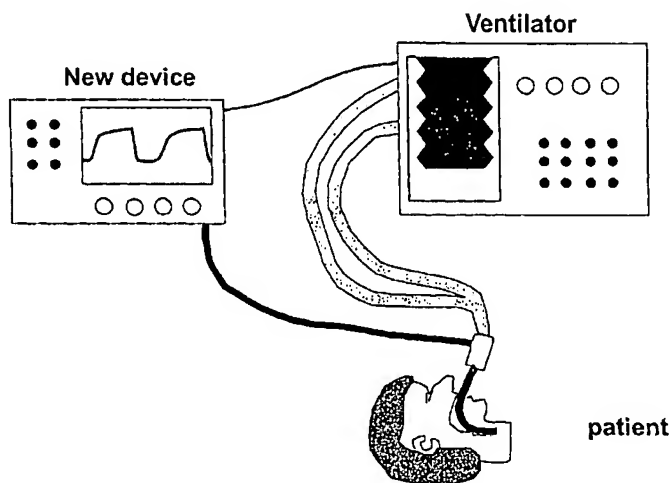
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(54) Title: **NON-INVASIVE METHOD AND APPARATUS FOR OPTIMIZING THE RESPIRATION OF ATELECTATIC LUNGS**



(57) Abstract: The invention concerns a method and apparatus for determining the status of a ventilated lung. For determining the status of a lung ventilated, which enables in real time optimal ventilatory settings for a recruitment maneuver of an ailing lung, the invention comprises a sensor for measuring a gas concentration in the expired gas during a single breath, an analog to digital converter for obtaining data samples of said gas concentration in the time domain, means for selecting a plurality of data samples, means for calculating a mean tracing value being sensitive to changes of alveolar dead space based on said samples, and a data processor which detects during a change of the airway pressure of the ventilator from the resulting course of calculated mean tracing values the peak inspiratory pressure at which alveolar opening or lung overdistension occurs and/or the PEEP at which lung open condition or alveolar closing occurs.

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**Non-Invasive Method and Apparatus for Optimizing the  
Respiration of Atelectatic Lungs**

The invention refers to a method and an apparatus for  
10 determining the status of a lung ventilated by an  
artificial ventilator.

Such a method and such an apparatus are known from WO  
00/44427 A1. WO 00/44427 A1 deals with the problem of the  
15 artificial ventilation of patients with an ailing lung. The  
basic patho-physiological mechanism of an ailing lung is  
the lack of surfactant (substance which reduces surface  
tension) which can cause a collapse of major lung fractions  
and a dramatically reduced gas exchange area. Hence, to  
20 prevent undesirable sequelae and consecutive multiorgan  
failure, an important goal of protective ventilator therapy  
is a gentle and early „reopening" of the lung. Through the  
identification of the alveolar opening and especially of  
the alveolar closing pressures, a distressed lung may be  
25 kept open by proper choice of the airway pressure. However,  
the manual determination of opening and closing pressures  
is arduous and time consuming. Therefore, WO 00/44427 A1  
suggests to use the partial pressures of oxygen ( $\text{paO}_2$ ) as  
an indicator for determining the opening and closing  
30 pressures of the lung. WO 00/44427 A1 has recognized that  
there is a significant hysteresis behaviour of the  $\text{paO}_2$  as  
a function of the ventilation pressure.

Fig. 1 shows the  $\text{paO}_2$  hysteresis of the same healthy (left)  
35 and ailing (right) lung. While there is almost no

hysteresis in the healthy lung and the choice of ventilation pressures has no visible impact on the quality of gas exchange, the hysteresis is even more severe in an ailing lung. In many cases, gas exchange may be reduced so strongly that at typical ventilation pressures, a sufficient hemoglobin oxygen saturation (> 85 mm Hg) may only be reached if high oxygen concentrations (e.g. 90 ... 100 %) are delivered to the patient.

For such an ailing lung, a ventilation strategy could be to first open the lung with a temporary high inspiratory airway pressure and then ventilate on the descending branch of the hysteresis such that a sufficient tidal volume is reached and gas exchange is maintained. This so called recruitment maneuver has become a common strategy in operating rooms and in the intensive care medicine. In general, to achieve a sufficient tidal volume it is necessary to ventilate the lung with a certain delta pressure, which is defined as:

20

$$\text{delta pressure} = \text{PIP} - \text{PEEP}$$

PIP is the peak inspiratory pressure and PEEP is the positive end expiratory pressure. The aim of the recruitment maneuver is to find the alveolar opening pressure and the alveolar closing pressure. It is then possible to set the peak inspiratory pressure slightly higher than the alveolar opening pressure and to set the positive end expiratory pressure slightly higher than the alveolar closing pressure. In this way ideally all previously closed lung units will be re-opened and at the same time all open lung units will be kept open.

During a recruitment maneuver the peak inspiratory pressure is stepwise increased so that as many lung units as

possible are re-opened, while at the same time the positive end expiratory pressure is increased in order to keep the newly recruited lung units open. When recruiting a lung, some lung units open up and become overdistended, while  
5 other lung units are still closed. Thus, when increasing the peak inspiratory pressure in order to re-open as many lung units as possible, most of the opened lung units will be overdistended.

10 Due to the hysteresis behaviour of the lung, the values obtained for peak inspiratory pressure and for the positive end expiratory pressure during this process of a stepwise increase are too high to further ventilate the lung once the lung units are opened. Thus they need to be reduced  
15 systematically.

At first the excessive peak inspiratory pressure is reduced while the positive end expiratory pressure is maintained at its level. This reduction is performed until an adequate  
20 tidal volume is reached. From this point onwards both the peak inspiratory pressure and the positive end expiratory pressure are reduced simultaneously. The aim is to find the lowest value for the positive end expiratory pressure that would just maintain all re-opened lung units open. At this  
25 stage the peak inspiratory pressure is a secondary variable of interest. Noticeably, the tidal ventilation will change during this simultaneous reduction of the peak inspiratory pressure and the positive end expiratory pressure, since the relief of overdistension will initially increase the  
30 lung's compliance. Once the positive end expiratory pressure is too low to keep all previously re-opened lung units open, the point of alveolar closing is reached.

Having identified the values of the peak inspiratory  
35 pressure corresponding to the alveolar opening pressure and

the positive end expiratory pressure corresponding to the alveolar closing pressure as outlined above, it is then possible to ventilate the lung in an optimal condition. First, all lung units are re-opened by choosing a peak  
5 inspiratory pressure which is slightly higher than the alveolar opening pressure, i.e. 2 - 5 cmH<sub>2</sub>O higher, and choosing a positive end expiratory pressure which is slightly higher than the alveolar closing pressure, i.e. 2 - 3 cmH<sub>2</sub>O higher. Afterwards the peak inspiratory pressure  
10 is reduced again to achieve the desired tidal volume. The corresponding ventilation stage corresponds to the optimal condition. An optimal compliance is achieved, since all lung units are opened, and no major overdistension is present.

15

By way of an example, Fig. 2 shows a typical recruitment maneuver in detail. As shown in Fig. 2, the recruitment maneuver is carried out on the basis of a pressure controlled ventilation. Before the final recruitment  
20 maneuver takes place, the alveolar opening pressure and the alveolar closing pressure have to be identified. In a first step (step 1), PIP and PEEP are stepwise increased by means of an incremental limb until the alveolar opening pressures have been detected with regard to PIP and PEEP (steps 2 and  
25 3). The alveolar opening pressure with regard to PIP is usually about 40 cmH<sub>2</sub>O in normal lungs and in the range of 55-60 cmH<sub>2</sub>O in sick lungs. After a successful alveolar opening, a decremental limb or stepwise decrease of PIP and PEEP is done (step 4) to determine the alveolar closing  
30 pressure (step 5). As outlined above initially only PIP is reduced as indicated at the transition from step 3 to step 4 in Fig. 2. After having identified the pressures for alveolar opening and alveolar closing, the final recruitment maneuver (step 6) is done with these new target  
35 pressures over 10 breaths and PEEP is set above the

alveolar closing pressure to avoid pulmonary re-collapse.  
For example, PEEP is set 2 cmH<sub>2</sub>O above the alveolar closing pressure, i.e.

$$5 \quad \text{PEEP} = \text{PEEP}_{\text{close}} + 2 \text{ cmH}_2\text{O}$$

Alternatively, a volume controlled ventilation can be carried out having the advantage that the ventilated volume remains constant and that all changes of the lung status  
10 can be related to changes within the alveoli.

In order to avoid the invasive measurement of paO<sub>2</sub>, WO 00/44427 A1 utilizes according to a first embodiment the endtidal CO<sub>2</sub> concentration (etCO<sub>2</sub>) and/or the CO<sub>2</sub> output as  
15 feedback signals for identification of the optimal ventilator settings for ailing lungs. Both feedback signals can be measured non-invasively. etCO<sub>2</sub> can be obtained by measuring the CO<sub>2</sub> concentration at the end of an expiration cycle. CO<sub>2</sub> output (unit [ml CO<sub>2</sub>/min]) can be obtained from  
20 continuous measurements of the CO<sub>2</sub> concentration (unit [%]) and air flow (unit [ml/min]) and subsequent breathwise computation of

$$\dot{V}_{\text{CO}_2 \text{ Atem}} = RR \cdot \int_0^T [\text{CO}_2](t) \cdot \dot{V}_{\text{Atem}}(t) DT$$

25

during one expiration cycle. According to a second embodiment of WO 00/44427 A1, the hemoglobin oxygen saturation (SO<sub>2</sub>) is measured non-invasively and is used as a feedback signal for identification of optimal ventilation  
30 parameters for ailing lungs.

In summary, WO 00/44427 A1 discloses a non-invasive method for determining the alveolar opening or closing of a lung based on one of the measurement of the parameters CO<sub>2</sub>

concentration ( $\text{etCO}_2$ ),  $\text{CO}_2$  output or hemoglobin oxygen saturation ( $\text{SO}_2$ ). However, practical tests have shown various disadvantages of this method. One disadvantage is the fact that a single parameter is subject of various  
5 disturbances so that an average value of several parameters has to be taken over several breath cycles which causes a delay in the feed back path. Another disadvantage is the fact that the detection of alveolar opening cannot be clearly distinguished from an overdistension of the lung  
10 which could cause severe damages to the lung during the recruitment maneuver.

Therefore, it is an object of the invention to provide a method and an apparatus for determining the status of a  
15 lung ventilated by an artificial ventilator which enables in real time optimal ventilatory settings for a well-conducted recruitment maneuver of an ailing lung.

A method according to the invention for determining the  
20 status of a lung ventilated by an artificial ventilator comprises the following steps:

- a) obtaining data samples of a gas concentration of the expired gas over a single breath,  
25
- b) selecting a plurality of data samples from said obtained data samples,
- c) calculating a mean tracing value being sensitive to  
30 changes of alveolar dead space on the basis of said selected data samples,
- d) repeating steps a), b) and c) for obtaining a plurality of mean tracing values, and

e) changing the peak inspiratory pressure and the positive end expiratory pressure of the artificial ventilator, wherein from the observation of the resulting course of the plurality of calculated mean tracing values the peak inspiratory pressure at which alveolar opening or lung overdistension and/or the positive end expiratory pressure at which lung open condition or alveolar closing occurs are detected.

10 An apparatus according to the invention for determining the status of a lung ventilated by an artificial ventilator comprises the following features:

a sensor for measuring a gas concentration in the expired gas during a single breath,

an analog to digital converter for obtaining data samples of said gas concentration of the expired gas over a single breath in the time domain,

20 means for selecting a plurality of data samples from said obtained data samples,

means for calculating a mean tracing value being sensitive to changes of alveolar dead space on the basis of said selected data samples, and

a data processor which detects during a change of the airway pressure of the artificial ventilator from the resulting course of a plurality of calculated mean tracing values the peak inspiratory pressure at which alveolar opening or lung overdistension occurs and/or the positive end expiratory pressure at which lung open condition or alveolar closing occurs.

35

According to a preferred aspect of the invention, the gas concentration represents the CO<sub>2</sub> concentration. The CO<sub>2</sub> concentration can be obtained using a CO<sub>2</sub> single breath test as described below. However, the CO<sub>2</sub> single breath  
5 test was developed for specific applications and therefore was restricted to evaluate the CO<sub>2</sub> concentration over a single breath. In contrast to that, it was found out that other gas concentrations over a single breath could be also used for the purpose of the invention since the invention  
10 is based on the hypothesis that a lung recruitment maneuver would reduce alveolar dead space. Starting from this hypothesis, the basic principle of the invention is to derive a mean tracing value from the gas concentration in the expired gas during a single breath which is sensitive  
15 to changes of alveolar dead space. As mentioned above, in the following the CO<sub>2</sub> concentration will be used exemplary.

The meaning of alveolar dead space with regard to the CO<sub>2</sub> concentration in the expired gas was already studied by R.  
20 Fletcher, G. Johnson and J. Brew in: "The Concept of Deadspace with Special Reference to Single Breath Test for Carbon Dioxide." Br. J. Anaesth., 53, 77, 1981 and will be explained further below with regard to Fig. 3.

25 Fig. 3 shows a plot of expiratory gas CO<sub>2</sub> concentration against expired volume, which can be obtained by combining a CO<sub>2</sub> concentration measurement against time and a volume rate measurement against time. This plot is called the CO<sub>2</sub> single breath test and shows three distinct phases in  
30 breath CO<sub>2</sub> gas concentration during the patient exhale cycle. Phase I represents CO<sub>2</sub> free gas expired from the airway conduction structures where gas exchange does not occur. Phase II is characterized by an S-shaped upswing and represents the transition from airway to alveolar gas.  
35 Phase III reflects the exhalation of unmixed gas from

regions of the lung which normally are in active exchange with the alveolar tissue and thus closely resembles at least in healthy patients gas properties associated with arterial blood in contact with the lung for gas exchange, i.e. CO<sub>2</sub> release and O<sub>2</sub> absorption. In normal lungs, Phase III is characterized by a horizontal level since ventilated and perfused alveolar regions are closely matched. In a diseased lung, Phase III may not appear horizontal due to a mismatch in ventilation and perfusion of this lung region.

10

The variables of the graph according to Fig. 3 have the following meaning:

- paCO<sub>2</sub> is the partial pressure of carbon dioxide.
- 15 etCO<sub>2</sub> is the endtidal CO<sub>2</sub> concentration of a single breath.
- X is the alveolar tidal volume and represents true alveolar gas which is the result of a gas exchange in the alveoli.
- 20 Y is the alveolar deadspace which is that part of inspired gas which reaches the alveoli but does not take part in gas exchange.
- Z is the airway deadspace which is that part of inspired gas which does not reach the alveoli and therefore does not take part in gas exchange
- 25 either.

The plot according to Fig. 3 is formed by the exhaled partial pressure of CO<sub>2</sub> against the expiratory tidal volume. Its analysis can be performed, e.g., using a side-stream infrared capnometer and a pneumotachograph of the Capnomac Ultima (e.g. Datex-Engstrom Instrument, Corp., Helsinki, Finland) or a main-stream CO<sub>2</sub> sensor (e.g. Novamatrix, USA). Furthermore, a computer is provided to

35 record and analyze data.

Before anesthesia and ventilating a patient, capnograph and blood gas analyzer should be calibrated using the same CO<sub>2</sub> concentration (5%). Airway flow can be measured and  
5 integrated to obtain volume. A corresponding device automatically normalizes airway volumes from standard condition to body temperature, ambient pressure and water vapor saturation (BTPS). Before anesthesia and ventilating a patient, induction the volume calibration can be done  
10 with e.g. a 700 ml super-syringe following the manufacturer's guidelines.

The side-stream CO<sub>2</sub> signal has a time delay with respect to the flow signal. A corresponding software can correct the  
15 CO<sub>2</sub> delays automatically using mathematical algorithms. The VTCO<sub>2,br</sub> or area under the curve can be computed by integrating expired flow and CO<sub>2</sub> in each breath. Analysis of dead space can be done on-line and/or off-line using Fowler's analysis and adding arterial PCO<sub>2</sub> values to the  
20 CO<sub>2</sub> curve of the single breath test.

A well known application of the CO<sub>2</sub> single breath test is the so called capnography, which is a technique to assess the arterial carbon dioxide content, expressed as partial  
25 pressure of CO<sub>2</sub> (paCO<sub>2</sub>), and which is disclosed in detail in WO 92/04865 A1 and WO 96/24285 A1. Since alveolar dead space cannot be derived directly from the CO<sub>2</sub> single breath test, both WO 92/04865 A1 and WO 96/24285 A1 assume alveolar dead space as a constant variable which has to be  
30 determined or estimated by other means, e.g. by a separate blood sample. Hence, according to WO 92/04865 A1 and WO 96/24285 A1 any changes of alveolar dead space are seen as a disturbance variable, since these changes result in a faulty estimate of paCO<sub>2</sub>.

In contrast to that the invention takes a new course for evaluating the CO<sub>2</sub> single breath test, since the invention uses now a mean tracing value which is sensitive to changes of alveolar dead space in order to determine certain lung conditions, namely alveolar opening or lung overdistension or lung open condition or alveolar closing. Hence, changes of alveolar dead space are no longer seen as a disturbance variable but are now taken as an indicator for certain lung conditions.

10 Since the meaning of alveolar dead space despite the well investigated single breath test with regard to the detection of alveolar opening or lung overdistension or lung open condition or alveolar closing of a ventilated lung was not recognized so far, the physiologic concept for alveolar dead space will be explained further below.

Fig. 4 shows the anatomical and functional units of the lungs, namely the lung acinus. The meaning of the abbreviations is as follows:

Cap = pulmonary capillary  
alv = alveolus  
Calv = alveolar duct  
25 Salv = alveolar sac  
RB = respiratory bronchiole.

The lung acinus is constituted of the respiratory bronchioli, alveolar ducts, alveolar sacs, alveoli and pulmonary capillaries. To maintain a normal function, this acinus must be well-ventilated and perfused, i.e. must be maintained in an open condition. If this acinus becomes collapsed, it loses its normal capacity for gas exchange and makes itself prone to injury during artificial ventilation, as stated previously.

Diffusion is a process fundamental to life because it is responsible for blood oxygenation and CO<sub>2</sub> removal within the lungs. Fig. 5 shows the diffusion phenomenon for CO<sub>2</sub> which is defined as a passive movement of CO<sub>2</sub> molecules through the alveolar-capillary membrane due to a gradient of concentration or partial pressures.

Diffusion is studied by Fick's law:

10

$$J = D_{mol} A Dc/Dx$$

where  $J$  is the instantaneous flux of CO<sub>2</sub>,  $D_{mol}$  represents the gas-phase molecular diffusivity of CO<sub>2</sub> in air,  $A$  is the area of gas exchange, and  $Dc$  the gas concentration gradient for CO<sub>2</sub> and  $Dx$  is the distance.

During normal physiology and in most of the pathological states,  $D_{mol}$ ,  $Dc$ , and  $Dx$  remain roughly constant. This means that the area ( $A$ ) becomes the main factor responsible for changes in the diffusion process within the lung.

The area of gas exchange depends on a normal acinar structure. Reduction in  $A$  is the consequence of pathologic three-dimensional changes in acinar morphology. Thus, a decrease in  $A$  as during lung collapse results in a decrease of the CO<sub>2</sub> and O<sub>2</sub> diffusion at the alveolar-capillary membrane. Opposite to that, the recovery of a normal acinar morphology by a recruitment maneuver normalizes  $A$  and thus diffusion.

According to the invention, the three-dimensional structural changes of the lung acini are reflected in a change of alveolar dead space during a CO<sub>2</sub> single breath test, wherein a suitable mean tracing value is used to

detect these changes. The mean tracing value represents a data fusion of the data samples of the CO<sub>2</sub> concentration using an average data algorithm. Examples of average data algorithms are a least squares linear regression, a  
5 weighted sum calculation or a FIR (finite impulse response) filter.

In contrast to WO 00/44427 A1 the method and the apparatus according to the invention has the advantage that an  
10 averaged value within one single breath is obtained which still yields a good accuracy for determining certain lung conditions. An important cognition of the invention compared to WO 00/44427 A1 is the fact that a plurality of data samples from said obtained data samples are selected  
15 which enables a selective evaluation of the CO<sub>2</sub> concentration within one single breath.

According to a preferred aspect of the invention, the data samples according to step a) are obtained in the time  
20 domain. This can be achieved by a conventional analog to digital converter. According to another preferred aspect of the invention, the obtained data samples are converted from the time domain into the volumetric domain. This is particularly useful for obtaining the well known plot of  
25 the CO<sub>2</sub> single breath test.

Fig. 6 shows some possible mean tracing values within a plot of a CO<sub>2</sub> single breath test, which are

slope III or endtidal mean slope	determined by the mean slope (either over time or over volume) of the CO <sub>2</sub> concentration in the expired gas towards the final stage of a single breath,
slope II or steepest mean slope	determined by the steepest mean slope (either over time or over volume) of the CO <sub>2</sub>

	concentration in the expired gas in vicinity of the point of inflection,
angle II-III	determined by the angle between slope II and slope III,
intercept II	determined by the intersecting point of slope II with the X-axis, and
intercept III	determined by the intersecting point of slope III with the Y-axis.

The following table shows an overview of these and some more mean tracing values together with their sensibility with regard to the lung stages "recruitment",

5 "overdistension", "open-lung" and "re-collapse":

Variable	recruitment	overdistension	open-lung	Re-collapse
$VD^{aw}$	$\uparrow\uparrow$ (+++)	$\uparrow\uparrow\uparrow$ (+++)	$\downarrow\downarrow$ (+)	$\downarrow\downarrow$ (+)
$VD^{aw}/VT$	$\uparrow\uparrow$ (+++)	$\uparrow\uparrow\uparrow$ (+++)	$\downarrow\downarrow$ (+)	$=\downarrow$ (+)
$VCO_2$	$\uparrow\uparrow$ (+++)	$\downarrow\downarrow$ (+++)	$\uparrow$ (+)	$=\downarrow$ (+)
$PAECO_2$	$\uparrow\uparrow$ (+++)	$\downarrow\downarrow$ (+++)	$\uparrow$ (+)	$=\downarrow$ (+)
$etCO_2$	$\uparrow\uparrow$ (+)	$=\downarrow$ (-)	$=\downarrow$ (-)	$\downarrow$ (-)
$VT_{CO_2,br}$	$\uparrow\uparrow$ (+++)	$\downarrow\downarrow$ (+++)	$\uparrow\uparrow$ (+)	$=\downarrow$ (+)
$VT^{alv}$	$\downarrow$ (+)	$\downarrow$ (-)	$\uparrow$ (-)	$=$ (+)
Angle II-III	$\downarrow\downarrow\downarrow$ (+++)	$\uparrow\uparrow\uparrow$ (+++)	$\downarrow\downarrow$ (+)	$\uparrow\uparrow\uparrow$ (+++)
Slope II	$\uparrow\uparrow\uparrow$ (+++)	$\downarrow\downarrow$ (+)	$\uparrow\uparrow$ (+)	$\downarrow\downarrow$ (+)

Variable	recruitment	overdistension	open-lung	Re-collapse
Slope III	↓↓↓ (+++)	↑ (-)	↓ (+)	↑↑ (+++)
Vol I	↑↑↑ (+++)	↑ (-)	↓ (+)	↓ (+)
Vol II	↑↑ (+++)	↑ (+)	↓↓ (+)	= ↑ (++)
Vol III	↓↓↓ (++)	↓ (+)	↑↑ (+)	= ↓ (+)
Intercept II	↓↓↓ (+++)	= ↓ (-)	↑ (+)	= ↑ (++)
Intercept III	↑↑↑ (+++)	↓ (+)	↑ (+)	= ↑ (-)

with:

- 5   =: no change  
      1 arrow: small change  
      2 arrows: moderate change  
      3 arrows: large change  
      (-): no sensitivity  
 10   (+): low sensitivity  
      (++): moderate sensitivity  
      (+++): high sensitivity.

The meaning of the variables with regard to their use as  
 15   mean tracing values is as follows:

VD<sup>aw</sup>: airway dead space. Is the dead space created by the  
 convective airways to the point where mixing with alveolar  
 gas takes place (Fig. 3, Z area). The midpoint of phase II  
 20   is the limit between anatomical dead space and alveolar gas  
 (Fowler's method). This midpoint is calculated as 50 % of

numerical data from slope II. It represents the gas inside the lung transported by convection.

VCO<sub>2</sub>: is the production of CO<sub>2</sub> per minute (ml/min) and is  
5 calculated as the product of the expired concentration of CO<sub>2</sub> by the alveolar minute ventilation.

VT<sub>CO<sub>2</sub>, br</sub>: or area under the curve, it represents the volume  
of CO<sub>2</sub> expired in a single breath measured by flow  
10 integration (Fig. 3, X area). It is useful to calculate CO<sub>2</sub> production. It represents the alveolar gas, which is in contact with pulmonary capillary blood.

Phase I: begins with the start of expiration (detection by  
15 a negative inflection on flow signal), and ends when the concentration of CO<sub>2</sub> in the CO<sub>2</sub> single breath test increases above 0,1 % from baseline (Fig. 3, Fig. 6).

Phase II: starts at the end of phase I (from 0,1 % CO<sub>2</sub>  
20 concentration) and continues to the intersection of the predictive slope lines for phases II and III (Fig. 3, Fig. 6).

Phase III: or alveolar plateau begins at the intersection  
25 of the predictive slopes lines for phase II and III and terminates at the end of expiration, defined by an abrupt positive deflection on flow signal (Fig. 3, Fig. 6).

Volume of phase I: Is the volume of gas contained in the  
30 phase I. It determines the largest part of the airway dead space and represents the gas in the proximal airway and the compressive gas in the ventilatory circuit (Fig. 3, Fig. 6).

Volume of phase II: Is the volume of gas contained in the phase II: The midpoint of phase II (50% of slope) is the limit between anatomical dead space and alveolar gas, and represents an interface when convective gas transport changes to diffusion transport in lung acini. Thus, phase II is part of both, airway dead space and alveolar gas. Phase II is highly influenced by the acinar emptying time: the more homogeneous the gas emptying for the acini the lower is the phase II volume (Fig. 3, Fig. 6).

Volume of phase III: This volume represents the gas inside the alveoli in contact with pulmonary capillary blood. It is considered as efficient volume for gas exchange within the tidal volume (Fig. 3, Fig. 6).

Slope of phase II: It is derived i.e. from least squares linear regression using data points collected between 25-75 % of the phase II, expressed as fraction (Fig. 6). The phase II slope of individual breaths is normalized by dividing the slope value by the corresponding mean alveolar fraction of CO<sub>2</sub> or PAECO<sub>2</sub> (expressed in %). Similar to volume of phase II, the slope represents the spread of acinar expiratory times. If all acini were emptying at almost the same time the ventilation would be more homogeneous and the slope increases. An opposite change in slope II represents an inhomogeneous gas emptying as observed i.e during atelectasis (lung collapse) (Fig. 6).

Slope of phase III: It is derived from e.g. least squares linear regression using data points collected between 25-75 % of the phase III, expressed as fraction (Fig. 6). The phase III slope of individual breaths is normalized by dividing the slope value by the corresponding mean alveolar fraction of CO<sub>2</sub> or PAECO<sub>2</sub> (expressed in %). Phase III slope is the most useful variable to measure a recruitment

effect. It is related to the ventilation/perfusion relationship ( $V/Q$ ): when the  $V/Q$  ratio is more efficient the phase III slope decreases, representing a decrease in  $CO_2$  diffusional resistance. When slope III increases, a  $V/Q$  mismatch is found.

Mathematical models have described the variables that can change phase III slope. They are: tidal volume, respiratory rate (only in the extreme of normal values), area of gas exchange, and gas diffusivity. Maintaining all variables stable that can change phase III slope, any change in the area of gas exchange can thus affect this slope. Fick's first law of diffusion can easily explain this statement.

Angle II-III: It is defined as the angle of intersection between slope of phase II and III. Changes in this angle represent changes of the shape of the  $CO_2$  single breath test related to the efficiency/inefficiency state of ventilation and gas exchange. When the angle decreases, as after lung recruitment, ventilation and gas exchange improve. Increasing angles II-III are related to an inhomogeneous (and worse) ventilation/perfusion relationship (Fig. 6).

Intercept of phase II slope: It is defined as the intersection of the line of phase II slope with the X axis (Fig. 6).

Intercept of phase III slope: It is defined as the intersection of the line of phase III slope with the Y axis (Fig. 6).

$V_{T^{alv}}$ : It represents the portion of tidal volume that is located distal to the interface, it is true alveolar gas.

This volume is constituted by the sum of  $VT_{CO_2}^{alv}$  plus  $VD^{alv}$ .  $VT^{alv}$  is derived by Fowler analysis as  $VT - VD^{alv}$ .

PAECO<sub>2</sub>: or mean expired concentration of CO<sub>2</sub>, constitutes  
5 the mean partial pressure of CO<sub>2</sub> in alveolar air. It is defined as the partial pressure of CO<sub>2</sub> at the middle of the slope III. This value represents the partial pressure of all CO<sub>2</sub> molecules in the expired volume.

10 etCO<sub>2</sub>: is the end tidal partial pressure of CO<sub>2</sub> (Fig. 3).

Pet-AECO<sub>2</sub>: is the difference between end tidal CO<sub>2</sub> and mean expired partial pressure. It is an index of alveolar dead space: the higher the differences between these two values,  
15 the higher is the inefficiency of lung function.

VDBohr: is the dead space formed by anatomical dead space plus part of the alveolar dead space (ml), defined as the lower portion of the alveolar dead space.

20

Vdaw/VT: the ratio between airway dead space to tidal volume, is an index of lung efficiency / inefficiency. The higher this index is the more inefficient the lung becomes.

25 It should be noted that Volume I, II, III and phase III slope are normalized by dividing them by the tidal volume to make comparison among different breaths possible.

According to a preferred aspect of the invention the  
30 endtidal mean slope is taken as a mean tracing value and is determined by the mean slope (either over time or over volume) of the CO<sub>2</sub> concentration in the expired gas towards the final stage of a single breath. The calculation of the endtidal mean slope can be carried out on the basis of a  
35 least squares linear regression using suitable constraints,

wherein a suitable constraint could be a minimum mean square error of the regression result over a predetermined range. On the basis of such a constraint the calculation of the endtidal mean slope would be carried out as follows:

5

Step 1: Performing on the basis of the data points of the measured CO<sub>2</sub> concentration of a single breath a running least squares linear regression over a predetermined range (either with regard to volume or time), wherein the predetermined range is a certain percentage of the expired volume or of the respiratory period, e.g. 20%.

10

Step 2: Identifying the range for which the mean square error of the running least squares linear regression becomes a minimum towards the final stage of a single breath.

15

Step 3: Setting the slope of the least squares linear regression over the identified range of step 2 as the mean tracing value of said single breath.

20

According to a preferred aspect of the invention, the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath starting from alveolar closing, wherein an alveolar opening of the lung is detected, if the resulting course of the plurality of determined first mean tracing values reaches a minimum.

25

According to another preferred aspect of the invention, the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath starting from alveolar opening, wherein a lung overdistension is detected, if the positive gradient of the resulting course of the plurality of determined first mean tracing values reaches a maximum.

30

35

According to another preferred aspect of the invention, the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath starting  
5 from lung overdistension, wherein an open lung condition is detected, if the resulting course of the plurality of determined first mean tracing values reaches a minimum.

According to another preferred aspect of the invention, the  
10 positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath starting from an open lung condition, wherein an alveolar closing is detected, if the positive gradient of the resulting course of the plurality of determined first mean tracing values  
15 reaches a maximum.

According to another preferred aspect of the invention a second mean tracing value is represented by the steepest mean slope of the CO<sub>2</sub> concentration in the expired gas  
20 during a single breath. The steepest mean slope is determined by the mean slope (either over time or over volume) of the CO<sub>2</sub> concentration in the expired gas in the vicinity of the point of inflection. The calculation of the steepest mean slope can be carried out again on the basis  
25 of a least squares linear regression using suitable constraints, wherein a suitable constraint could be a minimum mean square error of the regression result over a predetermined range. On the basis of such a constraint the calculation of the steepest mean slope would be carried out  
30 as follows:

Step 1: Performing on the basis of the data points of the measured CO<sub>2</sub> concentration of a single breath a running least squares linear regression over a  
35 predetermined range (either with regard to volume

or time), wherein the predetermined range is a certain percentage of the expired volume or of the respiratory period, e.g. 20%.

5 Step 2: Identifying the range for which the mean square error of the running least squares linear regression becomes a minimum in the vicinity of the point of inflection.

10 Step 3: Setting the slope of the least squares linear regression over the identified range of step 2 as the mean tracing value of said single breath.

According to another preferred aspect of the invention, the  
15 peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath starting from alveolar closing, wherein an alveolar opening of the lung is detected, if the resulting course of the plurality of determined second mean tracing values reaches a maximum.

20

According to another preferred aspect of the invention, the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath starting from alveolar opening, wherein a lung overdistension is detected, if the  
25 negative gradient of the resulting course of the plurality of determined second mean tracing values reaches a minimum.

According to another preferred aspect of the invention, the positive end expiratory pressure of the artificial  
30 ventilator is decreased stepwise breath by breath starting from lung overdistension, wherein an open lung condition is detected, if the resulting course of the plurality of determined second mean tracing values reaches a maximum.

According to another preferred aspect of the invention, the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath starting from an open lung condition, wherein an alveolar closing is detected, if the negative gradient of the resulting course of the plurality of determined second mean tracing values reaches a minimum.

According to another preferred aspect of the invention a third mean tracing value is represented by the angle between the endtidal mean slope and the steepest mean slope of the CO<sub>2</sub> concentration in the expired gas during a single breath.

According to another preferred aspect of the invention, the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath starting from alveolar closing, wherein an alveolar opening of the lung is detected, if the resulting course of the plurality of determined third mean tracing values reaches a minimum.

According to another preferred aspect of the invention, the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath starting from alveolar opening, wherein a lung overdistension is detected, if the positive gradient of the resulting course of the plurality of determined third mean tracing values reaches a maximum.

According to another preferred aspect of the invention, the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath starting from lung overdistension, wherein an open lung condition is detected, if the resulting course of the plurality of determined third mean tracing values reaches a minimum.

According to another preferred aspect of the invention, the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath starting from an open lung condition, wherein an alveolar closing is detected, if the positive gradient of the resulting course of the plurality of determined third mean tracing values reaches a maximum.

According to another preferred aspect of the invention, a plurality of different types of mean tracing values are calculated in parallel and wherein from the resulting course of the plurality of different types of mean tracing values the peak inspiratory pressure at which alveolar opening or lung overdistension and/or the positive end expiratory pressure at which lung open condition or alveolar closing occurs are detected.

According to another preferred aspect of the invention, during a recruitment maneuver of the lung the peak inspiratory pressure is set above the peak inspiratory pressure at which alveolar opening has been detected and the positive end-expiratory pressure is set above the positive end expiratory pressure at which alveolar closing has been detected.

25

Other objects and features of the invention will become apparent by reference to the following specification and to the drawings in which Fig. 1 to Fig. 6 have been referred to already in the introductory part of the description and in which Fig. 7 to Fig. 12 will be explained now in further detail.

Fig. 1 shows two graphs of the  $paO_2$  hysteresis of the same healthy (left) and ailing (right) lung,

35

- Fig. 2 shows a plot of the airway pressures over time of a typical recruitment maneuver,
- Fig. 3 shows a plot of the CO<sub>2</sub> single breath test with three distinct phases in breath CO<sub>2</sub> gas concentration during the patient exhale cycle,
- Fig. 4 shows a schematic diagram of the anatomical and functional units of the lungs,
- Fig. 5 shows a schematic diagram of the diffusion phenomenon for CO<sub>2</sub> in a human's lung,
- Fig. 6 shows some possible mean tracing values within a plot of a CO<sub>2</sub> single breath test,
- Fig. 7 shows two plots of a CO<sub>2</sub> single breath test in the states of atelectasis and recruitment,
- Fig. 8 shows a plot of the airway pressures over time of a typical recruitment maneuver together with the response of the steepest mean slope as a mean tracing value,
- Fig. 9 shows a plot of the airway pressures over time of a typical recruitment maneuver together with the response of the volume of phase II as a mean tracing value,
- Fig. 10 shows measurements of the partial pressure of oxygen (paO<sub>2</sub>) with 12 patients at three different lung stages,
- Fig. 11 shows measurements of the end-expiratory lung volume (EELV), the partial pressure of oxygen

( $\text{paO}_2$ ) and the compliance at three different ventilation modes,

5 Fig. 12 shows a draft of an apparatus according to the invention connected in series with the ventilator to the patient,

10 Fig. 13 shows a plot of the  $\text{O}_2$  single breath test depicting the  $\text{O}_2$  gas concentration during the patient exhale cycle,

15 Fig. 14 shows a plot comparing the  $\text{CO}_2$  gas concentration during a  $\text{CO}_2$  single breath test with the  $\text{O}_2$  gas concentration during an  $\text{O}_2$  single breath test during the patient exhale cycle, and

Fig. 15 shows some possible mean tracing values within a plot of an  $\text{O}_2$  single breath test.

20 Fig. 7 shows two plots of a  $\text{CO}_2$  single breath test in the states of atelectasis and recruitment. As it can be seen, an increase in the area of gas exchange due to recruitment alters the shape of the plot of a  $\text{CO}_2$  single breath test, wherein the endtidal mean slope (slope III) decreases and  
25 the steepest mean slope (slope II) increases. Hence, taking into account the above theoretical explanation, the reversible and dynamic acinar change in morphology can be manipulated by treatment. Normalizing acinar morphology in a mechanically ventilated patient by a recruitment maneuver  
30 produces a normalisation in the physiology of the lung. A normalisation in acinar morphology by the recruitment maneuver causes an improvement in gas exchange and in gas emptying during expiration.

Fig. 8 shows a plot of the airway pressures over time of a typical recruitment maneuver together with the response of the steepest mean slope (slope II) as a mean tracing value. The algorithm for diagnosing the lung's open-collapse state is described with regard to the steepest mean slope as follows:

1. Analysis of the baseline situation  
An analysis of the CO<sub>2</sub> single breath test is performed before the recruitment maneuver. This data are considered as the control values for comparison with values observed during and after the recruitment maneuver.
2. Analysis of lung recruitment  
During the recruitment maneuver the behavior of the steepest mean slope in each breath is observed and typical recruitment effects are detected.
3. Analysis of lung-overdistension  
At the end of the incremental limb of the recruitment maneuver the behavior of the steepest mean slope in each breath is observed and typical overdistension effects are detected.
4. Analysis of the open-lung condition  
During the decreasing limb of the recruitment maneuver the steepest mean slope is analyzed in every breath searching for changes representing the open-lung condition.
5. Analysis of the lung re-collapse  
During the decreasing limb of the recruitment maneuver the steepest mean slope is analyzed in every breath searching for changes representing lung re-collapse.
6. Final recruitment maneuver

A new recruitment maneuver is done with the known opening and closing pressure.

Although the algorithm merely has been described with  
5 regard to the steepest mean slope as a mean tracing value,  
it goes without saying that any other suitable mean tracing  
values as listed above or combinations thereof can be taken  
as a basis for carrying out the algorithm.

10 Fig. 9 shows a plot of the airway pressures over time of a  
typical recruitment maneuver together with the response of  
the volume of phase II as a mean tracing value. Lung  
recruitment, overdistension, open-lung condition and re-  
collapse are seen during the recruitment maneuver. The  
15 inflection point represents the change of direction of the  
volume of phase II from the open-lung condition to the  
beginning of the collapsed state. Furthermore, the  
inflection point represents the pulmonary closing pressure.

20 In the following, a first study concerning the effect of an  
alveolar recruitment strategy (ARS) on gas exchange and  
lung efficiency during one-lung ventilation (OLV) is  
discussed using the single breath test of CO<sub>2</sub>.

25 A total of 12 patients were studied during general  
anesthesia for elective open thoracic surgery or  
thoracoscopy. Patients with acute or chronic uncompensated  
cardiopulmonary disease were not included in the study.

30 Only for open thoracotomies, a thoracic epidural catheter  
was placed at T2 to T4 and a total volume of 0,1 ml/kg of  
bupivacaine 0,5% without epinephrine were administered.  
Prior to the epidural anesthesia, intravascular volume was  
expanded by infusing 7 ml/kg of a colloidal solution

(Haemacell™) and maintained at  $8 \text{ ml kg}^{-1} \text{ h}^{-1}$  of normal saline solution.

After 3 minutes of breathing 100 % oxygen, general  
5 anesthesia was induced with fentanyl  $5 \text{ } \mu\text{g/kg}$ , thiopental  $3 \text{ mg/kg}$  and vecuronium  $0,08 \text{ mg/kg}$  iv. Anesthesia was maintained with isofluorane  $0,5\text{-}0,6 \text{ MAC}$  and epidural lidocaine 1 % boluses of 5 ml for open thoracotomies. For  
10 thoracoscopies and minimal invasive coronary artery by-pass graft (mini-CABG), anesthesia was maintained with isofluorane  $0,7\text{-}1 \text{ MAC}$  and boluses of fentanyl  $2 \text{ } \mu\text{g/kg}$  and vecuronium  $0,015 \text{ mg/kg}$  as clinically necessary.

The trachea and the left bronchus were intubated with a left double lumen tube (DLT) of the appropriate size  
15 (Broncho-Cath™, Mallinckrodt Laboratories, Atholone, Ireland). Air leakage were assessed by introducing the capnograph's side stream sensor into each lumen of the DLT while maintaining ventilation through the other lumen. Bronchoscopy confirmed the correct position of the DLT  
20 before and after positioning the patients in the lateral position. During OLV, the lumen of the non-ventilated side was left open to atmosphere.

Lungs were ventilated with a Servo 900 C in a volume  
25 control ventilation mode and an inspired oxygen fraction ( $\text{FiO}_2$ ) of 1.0. The ventilator delivered a square-wave flow with an inspiratory time of 33% with no end-inspiratory pause. The respiratory rate was set between 10-14 breaths/min, tidal volumes ( $\text{VT}$ ) were maintained at  $8 \text{ ml/kg}$ ,  
30 and PEEP was  $8 \text{ cmH}_2\text{O}$  throughout the study.

During OLV, tidal volume was reduced to  $6 \text{ ml/kg}$  to avoid peak pressures higher than  $30 \text{ cmH}_2\text{O}$ . Respiratory rate was increased to 15-18 breaths/min to maintain the same minute  
35 ventilation as during TLV.

Standard monitoring was performed with the Cardiocap II monitor. A Capnomac Ultima monitor was used to measure the following ventilation parameters and gas concentrations:

5 Peak inspiratory pressure (PIP), PEEP, expired tidal volume (VTe), respiratory rate, expired minute volume, O<sub>2</sub> and CO<sub>2</sub> fractions.

Carbon dioxide elimination (VCO<sub>2</sub>) was calculated as the product of alveolar ventilation times the mean expired alveolar fraction of CO<sub>2</sub> (FAECO<sub>2</sub> %). Oxygen consumption (VO<sub>2</sub>) was calculated as the product of alveolar ventilation times the inspiratory-expiratory O<sub>2</sub> difference. Respiratory quotient (RQ) was calculated dividing VCO<sub>2</sub> by VO<sub>2</sub>. The

10 single breath analysis for CO<sub>2</sub> was performed using the sidestream infrared capnometer and the pneumotachograph of the Capnomac Ultima and a signal processor. Data were recorded and analyzed by a computer.

Capnograph and blood gas analyzer were calibrated using a known gas concentration of CO<sub>2</sub> (5%). This calibration was performed in each patient before the induction of anesthesia. Airway flow and pressure measurements are based on the measurement of kinetic gas pressure, and are

20 performed using the Pitot effect. Flow rate is measured and integrated to obtain VT. The Capnomac device restores normal airway volumes from standard condition to body temperature, ambient pressure and water vapor saturation (BTPS) automatically. Volume calibration was done with a

25 700 ml super-syringe before anesthesia induction following the manufacturer's guidelines.

The sidestream CO<sub>2</sub> signal has a time delay compared to the flow signal. The software automatically corrected the CO<sub>2</sub>

35 delay using commonly known mathematical algorithms. The

VTCO<sub>2,br</sub> or area under the curve was computed by integrating expired flow and FCO<sub>2</sub> in each breath.

Analysis of dead space was done off-line using Fowler's  
5 analysis and adding PaCO<sub>2</sub> value to the CO<sub>2</sub> curve of the  
single breath test (Fig. 3). The mean value of 3  
consecutive CO<sub>2</sub> single breath tests was used for each  
variable. The dead space of the apparatus was 60 ml (10 ml  
from D-LITE™ plus 50 ml from DLT connections) and was  
10 subtracted from the airway dead space value.

All measurements were performed with the patient in the  
lateral position. Arterial blood gases, CO<sub>2</sub> single breath  
test data, ventilatory and hemodynamic data were recorded  
15 at three points:

- a) TLV: 15 minutes after placing the patient in the  
lateral position with the chest still closed.
- b) OLV<sub>PRE</sub>: after 20 minutes of OLV ventilation, before  
20 applying the ARS.
- c) OLV<sub>ARS</sub>: 20 minutes after applying the ARS selectively to  
the dependent lung.

Patients were studied during OLV prior to any vascular  
25 interruption in the non-dependent lung. During OLV patients  
were studied at the moment of highest shunt prior to any  
vascular clipping in the nondependent lung.

The recruitment maneuver was applied selectively to the  
30 dependent lung immediately after the measurement at point  
b. First, the ventilator was switched to pressure control  
ventilation, adjusting the level of pressure to obtain the  
same tidal volume as during volume control ventilation.  
Ventilation was then allowed to equilibrate for three  
35 minutes. Thereafter, the ARS was performed based on an

established concept. The critical alveolar opening pressure was assumed to be at 40 cmH<sub>2</sub>O as described for healthy lungs.

5   ARS protocol:

1. Inspiratory time was increased to 50 %.
2. Respiratory frequency was set to 12 breaths/min.
3. The inspiratory pressure gradient was limited to 20  
10 cmH<sub>2</sub>O in order to avoid large tidal volumes during the maneuver. PIP and PEEP were sequentially increased from 30/10 to 35/15 in steps of five breaths. The recruitment pressure of 40/20 cmH<sub>2</sub>O was applied for 10 breaths.
4. Airway pressures were then gradually decreased,  
15 returning to baseline settings but maintaining a PEEP level of 8 cmH<sub>2</sub>O.

After completing the ARS, the ventilator was set back to volume control. The ARS took about 3 minutes. Prior to the  
20 recruitment maneuvers central venous pressure values were maintained above 10 mmHg to avoid hemodynamic side effects caused by the increased intrathoracic pressures. Hemodynamic and ventilatory variables were monitored closely while performing the ARS. If mean arterial pressure  
25 and/or heart rate changed by more than 15 % from baseline, the ARS was discontinued and 500 ml of crystalloid solution were administered. After regaining hemodynamic stability the ARS was tried again.

30 During surgery, oxygen saturation was maintained above 90% at all times. If during OLV SpO<sub>2</sub> fell below 90%, surgery was temporarily interrupted to resume TLV (intermittent ventilation) until oxygen saturation recovered to at least 97 %. Blood samples were processed within 5 minutes of  
35 extraction by the blood gas analyzer known as ABL 520 and

values were corrected for body temperature. The calibration of this device was done with the same CO<sub>2</sub> concentration as the capnograph (5%).

- 5 Comparison of variables between points was carried out using repeated-measure analysis of variance. If the analysis of the variance F-statistic was significant the Student-Newman-Keuls post-test detected significant differences. Values are reported as mean  $\pm$  SD and a p < 10 0,05 was considered significant.

Twelve patients, 10 men and 2 women, were included in this study. The following table shows the patients data. Only patient number 7 received inhaled bronchodilators 15 sporadically as needed.

P	Age (yrs)	Gender	BMI (Kg/h <sup>2</sup> )	FEV <sub>1</sub> (Lts/%)	pH	PaO <sub>2</sub> (mmHg)	PaCO <sub>2</sub> (mmHg)	Smoking (p/Year)	Surgery
1	71	M	26	2,1/84	7.39	64	36	50	RUL
2	48	M	28	3,0/93	7.43	101	39	NO	RUL
3	57	F	24	2,4/101	7.43	91	40	NO	RML
4	65	M	23	---	7.40	84	44	NO	Thoracoscopy
5	66	M	29	2,5/85	7.36	95	39	30	Mini-CABG
6	72	F	23	1,8/73	7.44	81	39	25	Mini-CABG
7	73	M	26	1,7/67	7.50	73	38	41	LUL
8	73	M	27	1,9/78	7.35	84	42	22	Thoracoscopy
9	19	M	23	---	7.44	99	37	NO	Thoracoscopy
10	58	M	30	2,9/89	7.34	89	43	NO	RLL
11	74	M	28	2,2/79	7.48	75	41	45	RUL/RML
12	66	M	27	2,6/96	7.34	83	39	NO	Mini-CABG
Mean	62		26		7.41	85	40		
SD	15		2,4		0,06	11	2,3		

Age (years), BMI = body mass index (kg m<sup>-2</sup>)  
 FEV<sub>1</sub> (absolute values in liters and % of normal values),  
 20 smoking history measured in total pack-year (N° cigarettes  
 smoked per day / 20 x N° years of smoking). PaO<sub>2</sub>, PaCO<sub>2</sub> and

pH awake values at room air. In patients 4 and 9 respiratory tests were not performed due to pneumothoraces. L-L =left lung, R-L = right lung, L = lower lobe, U = upper lobe, M = median lobe.

5 Mini-CABG = minimal invasive coronary by-pass graft.

The following table shows the results with regard to the most relevant mean tracing values and at three different lung stages:

10

Variables	TLV	OLV before ARS	OLV after ARS
<b>Absolute values (ml):</b>			
VD <sup>aw</sup>	160 ± 28	123 ± 29 *	107 ± 30 †
VD <sup>alv</sup>	106 ± 31	107 ± 24	97 ± 23
VD <sup>phys</sup>	266 ± 42	230 ± 39	204 ± 34 †
VT <sup>alv</sup>	392 ± 42	260 ± 39 *	279 ± 40 †
VT <sub>CO<sub>2</sub>,br</sub>	19 ± 2,8	13 ± 2,7	14 ± 2,5
<b>Ratios:</b>			
VD / VT	0,50 ± 0,04	0,60 ± 0,05 *	0,53 ± 0,04 †
VD <sup>aw</sup> /VT	0,30 ± 0,05	0,33 ± 0,07	0,29 ± 0,08
VD <sup>alv</sup> /VT <sup>alv</sup>	0,28 ± 0,07	0,43 ± 0,1 *	0,35 ± 0,07
Vol I / VT	0,23 ± 0,03	0,24 ± 0,06	0,19 ± 0,04 ‡
Vol II / VT	0,29 ± 0,05	0,30 ± 0,05	0,25 ± 0,04 ‡
Vol III / VT	0,48 ± 0,07	0,47 ± 0,1	0,56 ± 0,07 ‡
Slope II (%/L)	16 ± 3,5	15 ± 3,9	18 ± 3,9
Slope III/N (1/L)	0,58 ± 0,3	1,08 ± 0,3 *	0,72 ± 0,2 ‡

wherein:

TLV = two lung ventilation

OLV<sub>PRE</sub> = one lung ventilation before the recruitment maneuver

5 OLV<sub>ARS</sub> = one lung ventilation after an alveolar recruitment strategy (ARS).

VD<sup>aw</sup> = airway dead space

VD<sup>alv</sup> = alveolar dead space

VD<sup>phys</sup> = physiological dead space.

10 VT<sup>alv</sup> = alveolar tidal volume

VT<sub>CO<sub>2</sub>,br</sub> = expired volume of CO<sub>2</sub> per breath

VD/VT = physiological dead space to tidal volume

VD<sup>aw</sup>/VT = airway dead space to tidal volume

VD<sup>alv</sup>/VT<sup>alv</sup> = alveolar dead space to alveolar tidal volume,

15 Vol I, II and III/VT = volume of phase I, II and III to tidal volume respectively, slope II = phase II slope (%/L) and slope III/N = normalized phase III slope (1/L) dividing absolute value by the mean alveolar fraction of CO<sub>2</sub> (FAECO<sub>2</sub>, in %).

20

The physiological dead space (VD<sup>phy</sup>) was calculated by Enghoff's modification of the Bohr equation, where  $VD^{phy}/VT = PaCO_2 - PAECO_2/PaCO_2$ . Alveolar dead space (VD<sup>alv</sup>) was calculated by subtracting physiological from airway dead  
25 space.

\* TLV against OLV<sub>PRE</sub>,  $p < 0,05$ ; † OLV<sub>ARS</sub> against TLV,  $p < 0,05$ ; and ‡ OLV<sub>ARS</sub> against OLV<sub>PRE</sub>,  $p < 0,05$ .

30 Fig. 10 shows measurements of the partial paO<sub>2</sub> pressure with 12 patients at three different lung stages.

PaO<sub>2</sub> was significantly higher during TLV ( $379 \pm 67$  mmHg) compared to OLV<sub>PRE</sub> ( $144 \pm 73$  mmHg,  $p < 0,001$ ) and OLV<sub>ARS</sub> ( $244 \pm 89$  mmHg,  $p < 0,001$ ). During OLV the difference in PaO<sub>2</sub>  
35

before and after the ARS also reached significance. Hemoglobin O<sub>2</sub> saturation was lower at OLV<sub>PRE</sub> ( $95,5 \pm 2,6 \%$ ) as compared to TLV ( $98,7 \pm 0,4\%$ ,  $p < 0,001$ ) and OLV<sub>ARS</sub> ( $97,8\% \pm 0,9\%$ ,  $p < 0,01$ ).

5

Only patients 8 needed 4 cycles of intermittent ventilation during OLV before the ARS ( $\text{SpO}_2 < 90\%$ ). Blood gases were taken after the fourth cycle of intermittent TLV immediately before the recruitment maneuver. In these  
10 patients the ARS relieved the arterial hypoxemia instantaneously, ( $\text{SpO}_2$  from 88% to 98%) and no more episodes of hemoglobin desaturation occurred.

PaCO<sub>2</sub> was  $43 \pm 6$  mmHg during OLV<sub>ARS</sub> but not significantly  
15 different from the other conditions. However, PaCO<sub>2</sub> was higher during OLV<sub>PRE</sub> ( $46 \pm 6$  mmHg) compared to TLV ( $38 \pm 4$  mmHg,  $p < 0,05$ ). EtCO<sub>2</sub> and PAECO<sub>2</sub> were stable during the protocol without any significant differences among the measurement points. Pa-etCO<sub>2</sub> difference was significant  
20 higher during OLV<sub>PRE</sub> ( $14,2 \pm 4,8$  mmHg) compared to TLV ( $8,8 \pm 3,2$  mmHg) and OLV<sub>ARS</sub> ( $11,6 \pm 4,6$  mmHg). The pH<sub>a</sub> remained in the normal range throughout the study period.

All mean tracing values (variables) listed in the table  
25 above decreased during OLV<sub>ARS</sub> compared to OLV<sub>PRE</sub>, but differences showed statistical significance only for VD/VT, Vol I, II, III/VT and phase III slope.

Tidal volumes were higher during TLV ( $506 \pm 83$  ml) compared  
30 to OLV<sub>PRE</sub> ( $377 \pm 45$  ml) and OLV<sub>ARS</sub> ( $382 \pm 42$  ml). Minute ventilation was similar between OLV<sub>PRE</sub> (5,9 l/min) and OLV<sub>ARS</sub> (5,8 l/min), but both values were significantly smaller than during TLV (7 l/min). PIP values were higher during OLV<sub>PRE</sub> ( $25,3 \pm 1,7$  cmH<sub>2</sub>O) compared with TLV ( $20,6 \pm 1,7$

cmH<sub>2</sub>O,  $p < 0,001$ ) and OLV<sub>ARS</sub> ( $23,2 \pm 2$  cmH<sub>2</sub>O,  $p < 0,05$ ) with no differences between the latter two.

Hemodynamic variables, minute CO<sub>2</sub> elimination, oxygen  
5 consumption and respiratory quotient were similar at all time points. The total time of OLV ranged from 50 to 105 minutes. No hemodynamic or ventilatory side effects related to the recruitment maneuver were detected.

10 The results of this study indicate an improved efficiency in gas exchange after a lung recruitment maneuver during OLV. This finding can be explained by a recruitment effect on both, shunt and dead space, taking into account that hemodynamic, metabolic and ventilatory conditions were  
15 stable along the protocol.

Arterial oxygenation is a common measurement used to describe the extent of lung collapse. It has been suggested that a PaO<sub>2</sub> higher than 450 mmHg defines an open lung  
20 condition during pure O<sub>2</sub> breathing. Arterial oxygenation, however, is an unspecific variable to evaluate the recruitment effect since it depends on the hemodynamic and metabolic status. As these two conditions remained stable throughout the study period, a true recruitment effect is  
25 the most likely explanation for the increases seen in PaO<sub>2</sub>.

During TLV a mean PaO<sub>2</sub> of  $379 \pm 67$  mmHg indicated some extent of lung collapse, which is a common finding during general anesthesia. Oxygenation was further impaired during  
30 OLV<sub>PRE</sub> but increased after recruiting the dependent lung.

At TLV, the calculated shunt values of the patients ranged from 8 to 22 % (mean 16 %), values typically seen in general anesthesia, during OLV from 18 to 45 % (mean 28 %)  
35 and during OLV<sub>ARS</sub> from 12 to 27 % (mean 21 %). After lung

recruitment oxygenation was sufficient to maintain hemoglobin saturation above 95 %.

5 PaCO<sub>2</sub> increased during OLV at the same etCO<sub>2</sub> and PAECO<sub>2</sub> values as those observed during TLV. Increases in dead-space during OLV can explain this decrease in the efficiency of CO<sub>2</sub> removal.

10 During TLV, the values of the dead space related mean tracing values are higher than normal, due to the double lumen tube, lung collapse, open-chest condition, and the use of positive pressure ventilation.

15 Surprisingly, alveolar dead space did not change during OLV despite a significant increase in shunt. There is no explanation for the absence of an increase in VD<sup>alv</sup> despite a marked shunt effect (apparent dead space) during OLV compared to TLV. It is assumed that during TLV a decrease in the perfusion of the nondependent lung can increase VD<sup>alv</sup> 20 (real alveolar dead space) despite a lower shunt.

Large tidal values during TLV result also in absolute large values for VD<sup>aw</sup>, VT<sup>alv</sup> and VD<sup>phys</sup> larger than the ones observed during OLV, thus making their direct comparison 25 questionable. Nevertheless, when these mean tracing values (variables) are adjusted to account for differences in tidal volume this comparison may become useful.

The mean tracing values (variables) that represent 30 efficiency of ventilation and CO<sub>2</sub> exchange (VCO<sub>2,br</sub>, VD/VT, Pa-etCO<sub>2</sub>, VT<sup>alv</sup>, VD<sup>alv</sup>/VT<sup>alv</sup>) were higher during TLV compared to OLV. During OLV all mean tracing values (variables) improved only after the recruitment maneuver. Even more interesting was the behaviour of the mean tracing values 35 (variables) that show the distribution of tidal volume

throughout the phases of the CO<sub>2</sub> single breath test. Distribution of volume was most efficient during OLV after the ARS as indicated by a decrease in phase I and II volumes and a concomitant increase in phase III volume. The  
5 absolute value of the ratio Phase III/VT observed after recruitment was even higher than during TLV. Phase II represents a transition between alveolar and airway gas transport. An increase in the cross-sectional area of the bronchial tree in the lung periphery decreases the linear  
10 velocity of the bulk flow until a point where the two transport mechanisms within the lungs (convection and diffusion) are of equal magnitude. This stationary diffusion front demarcates the transition between airway and alveolar gas. On expiration, this front corresponds to  
15 phase II and is used to measure  $VD^{aw}$  in Fowler's analysis.

Changes in inspiratory flow, tidal volume and peripheral cross-sectional area of bronchioli have an effect on the diffusion front, and thus on the volume and slope of phase  
20 II. If inspiratory flow and tidal volume are constant, as during OLV, any change in phase II must be interpreted as a recruitment related increase in the cross-sectional area of the bronchioli leading to a more homogeneous gas emptying of lung acini. The slope of phase II, which depends on the  
25 spread of transit time of different lung units, increased during OLV after the recruitment maneuver when compared to the other study conditions. However, differences were not significant. This increase in phase II slope in combination with a decrease in its volume, can be considered as a more  
30 synchronous and homogeneous emptying of acini during expiration. Both, asthma and emphysema would have an opposite effect on phase II. These conditions show a wide dispersion of the transit time of gas emptying among lung units making the slope of phase II flatter and its volume  
35 higher.

Diffusion is the most important mechanism of gas transport within the acinus. Phase III volume represents the amount of gas exposed to the capillary bed and therefore depends on an effective pulmonary perfusion and CO<sub>2</sub> production. Phase III slope is directly related to the V/Q relationship and represents the diffusional resistance for CO<sub>2</sub> at the alveolar-capillary membrane. Its positive slope is explained by lung pendelluft, continuous evolution of CO<sub>2</sub> from the blood into the acini, and a stratified inhomogeneity.

As could have been expected, during OLV<sub>ARS</sub>, phase III volume increased while its slope decreased compared to OLV<sub>PRE</sub>. Decrease in functional lung acini in emphysema is related to an increase in phase III slope.

The patients included in the study were submitted to different thoracic surgeries including classical thoracotomies (lobectomies), minimal invasive thoracotomies (mini-CABG), and closed-chest surgeries (Thoracoscopies). Possible differences in lung mechanics can account for the changes in arterial oxygenation and ventilation efficiency among these different type of surgeries. However, oxygenation and dead space behaviour were similar and hemodynamic and metabolic conditions were constant along the study period. For these reasons, it is assumed that the changes in gas exchange and dead space observed in the study were related to the therapeutic effect of the recruitment maneuver.

Epidural anesthesia used in open thoracotomies can cause hemodynamic and metabolic changes that could influence gas exchange. However, these conditions were stable and no

differences in  $\text{PaO}_2$  between open thoracotomies and thoracoscopies, without epidural anesthesia, were seen.

Empirical values of 40 cmH<sub>2</sub>O of PIP were used as opening  
5 pressure and 8 cmH<sub>2</sub>O of PEEP to keep the lung open, since individual levels of these pressures for each patient are difficult to determine at the bedside.

Due to a mediastinal displacement, the surgeon's  
10 manipulation and the chest fixation opening and closing pressures in the dependent lung could be higher during thoracic surgery as compared to the other types of surgeries. In addition, PIP pressure may not represent true alveolar pressure when using a narrow DLT. For these  
15 reasons, it is possible that true opening and closing pressures were not reached in each patient which could have resulted in the absence of the maximal impact of the ARS on oxygenation and lung efficiency.

20 Lung recruitment improves gas exchange and ventilation efficiency during OLV anesthesia. The results suggest that one simple recruitment maneuver during OLV is enough to increase  $\text{PaO}_2$  to safer levels thereby eliminating the need for any additional therapeutic intervention.

25

In the following, a second study concerning the effect of PEEP on dead space, with and without a lung recruitment maneuver, is discussed.

30 Sixteen patients were studied prospectively undergoing open lower abdominal surgery. The enrolled patients were patients ASA II-III, without smoking history or cardiopulmonary uncompensated diseases.

Anesthesia induction was performed with fentanyl 4  $\mu\text{g kg}^{-1}$ ,  
35 thiopental 3  $\text{mg kg}^{-1}$  and vecuronium 0,08  $\text{mg kg}^{-1}$  and

maintained with Isoflurane and bupivacaine 0,5% through an epidural catheter inserted at L2-3.

After tracheal intubation with a cuffed endotracheal tube,  
5 the lungs were ventilated with a Siemens 900 C ventilator  
(Siemens-Elema, Solna, Sweden). Air leaks from around the  
endotracheal tube were detected by comparing inspired-  
expired tidal volume (VT) measured proximally in the  
airway. A volume controlled mode was used with a VT of 8 ml  
10  $\text{kg}^{-1}$ , respiratory rate (RR) between 10 -15 bpm,  $\text{FIO}_2$  of 0,5,  
inspiratory time of 0,3 without pause and initially,  
without positive end-expiratory pressure (ZEEP). Alveolar  
ventilation was increased or decreased by adjusting RR to  
reach an end-tidal  $\text{CO}_2$  value of 34 mmHg while maintaining  
15 VT constant.

Static respiratory compliance was measured dividing VT by  
the pressure differences between plateau and total PEEP.  
End-expiratory lung volume (EELV) was measured pushing the  
20 expiratory pause button of the Servo 900C for 6 seconds  
during the inspiratory pause while releasing PEEP from 5  
 $\text{cmH}_2\text{O}$  to ZEEP. Thus, a volume of gas is expelled until FRC  
at ambient pressure is reached. The EELV was then  
determined by subtracting the average value of the latest  
25 three normal expiratory tidal volumes before the maneuver  
from the volume of gas measured. This volume was recorded  
continuously in a computer and analyzed it off-line. The  
return of the expiratory flow curve to baseline at the end  
of the EELV-maneuver was used for checking air trapping.

30

Carbon dioxide elimination ( $\text{VCO}_2$ ) was calculated by  
multiplying alveolar ventilation and mean alveolar fraction  
of  $\text{CO}_2$ . Oxygen consumption ( $\text{VO}_2$ ) was calculated as the  
product of alveolar ventilation and inspiratory-expiratory  
35  $\text{O}_2$  difference. The respiratory quotient (RQ) was calculated

dividing  $\text{VCO}_2$  by  $\text{VO}_2$ . The  $\text{CO}_2$  single breath test and its mean tracing values are explained according to Fig. 3 and Fig. 6 above.

- 5 The ventilatory, hemodynamic and metabolic states were maintained constant during the study. In each patient 3 periods were studied sequentially:
1. ZEEP: ventilation with zero of PEEP.
  2. PEEP: ventilation with 5  $\text{cmH}_2\text{O}$  of PEEP.
  - 10 3. ARS: Between point 2 and 3, the lungs were ventilated for 20 minutes without PEEP to reach baseline conditions once again.

The alveolar recruitment strategy is a maneuver assigned to  
15 treat pulmonary collapse by reaching the alveolar opening pressure for ten breaths and keeping the lung open with a PEEP level above the lung's closing pressure. In the patients studied it is assumed that the lung opening pressure was 40  $\text{cmH}_2\text{O}$  of peak inspiratory pressure (PIP)  
20 and the closing pressure lower than 5  $\text{cmH}_2\text{O}$ . The maneuver was performed according to Fig. 2 with the following settings:

- Ventilatory frequency was set to 15 breaths per minute.
- 25 - Inspiration/expiration ratio was set at 1:1.
- Delta pressure or the pressure difference between PIP and PEEP (PIP/PEEP) was maintained at 20  $\text{cmH}_2\text{O}$ .
- Airway pressures were increased in steps: 25/5 to 30/10 and then to 35/15  $\text{cmH}_2\text{O}$ . Each step of pressure was  
30 maintained for 5 breaths.
- A final PIP/PEEP step of 40/20  $\text{cmH}_2\text{O}$  was reached and maintained for 10 breaths.
- After the 10 breaths, airway pressures were gradually decreased returning to the previous setting at 5  $\text{cmH}_2\text{O}$   
35 of PEEP reassuming a volume controlled ventilation

mode.

At the end of each period (30 minutes), the CO<sub>2</sub> single breath test curves were recorded and blood samples taken  
5 for dead space analysis. Blood specimens were processed and corrected for body temperature within 5 minutes of extraction by a gas analyzer ABL 510. Body temperature was measured with an esophageal thermometer.

10 Comparison of mean tracing values (variables) among periods was carried out using analysis of variance. If the variance F-statistic was significant the Student-Newman-Keuls post-test detected significant differences. EELV between PEEP and ARS was evaluated by the Student t test. Values are  
15 reported as mean  $\pm$  SD and a  $p < 0,05$  was considered significant.

Nine females and seven males, aged 65-80 years ( $71,2 \pm 4,5$ ), with body mass indices between 24-30 ( $26,8 \pm 2,1$ )  
20 undergoing hysterectomies ( $n = 3$ ) and hemicolectomies ( $n = 13$ ) were studied. The following table shows the detected mean tracing values (variables) with regard to the three different ventilation modes ZEEP, PEEP and ARS, where:

25 VD/VT = physiologic dead space to tidal volume  
VDAW = airway dead space (ml)  
VDALV = alveolar dead space (ml)  
VDPHYS = physiologic dead space (ml)  
VDAW / VTALV = alveolar dead space to tidal volume  
30 VDAW/VT = airway dead space to tidal volume  
VTCO<sub>2,br</sub> = CO<sub>2</sub> elimination per breath (ml)  
VTALV = alveolar tidal volume (ml)  
Vol I/VT = volume of phase I to tidal volume  
Vol II/VT = volume of phase II to tidal volume  
35 Vol III/VT = volume of phase III to tidal volume

slope II = phase II slope

slope III/N = normalized phase II slope divided by the mean alveolar concentration of CO<sub>2</sub>

angle II/III = angle formed between phase II and III slopes

5 (°).

\* PEEP against ZEEP,  $p < 0,05$

† ARS against ZEEP,  $p < 0,05$

‡ ARS against PEEP,  $p < 0,05$ .

Values are presented as mean  $\pm$  SD. A p value lower than  
10 0,05 was considered significant.

Variable	ZEEP	PEEP	ARS
V <sub>D</sub> /V <sub>T</sub>	0,50 $\pm$ 0,07	0,51 $\pm$ 0,06	0,45 $\pm$ 0,01 *†
V <sub>D AW</sub> (ml)	160 $\pm$ 48	161 $\pm$ 38	137 $\pm$ 32
V <sub>D ALV</sub> (ml)	110 $\pm$ 35	113 $\pm$ 30	108 $\pm$ 32
V <sub>D PHYS</sub> (ml)	270 $\pm$ 54	274 $\pm$ 56	246 $\pm$ 50
V <sub>D ALV</sub> /V <sub>TALV</sub>	0,29 $\pm$ 0,05	0,28 $\pm$ 0,06	0,26 $\pm$ 0,04
V <sub>DAW</sub> /V <sub>T</sub>	0,30 $\pm$ 0,08	0,29 $\pm$ 0,04	0,25 $\pm$ 0,04 ‡†
V <sub>T CO<sub>2</sub>,br</sub> (ml)	23 $\pm$ 2,6	25 $\pm$ 3,3 *	27 $\pm$ 3,2 ‡†
V <sub>T ALV</sub> (ml)	340 $\pm$ 72	355 $\pm$ 71	373 $\pm$ 68 ‡†
Vol I / V <sub>T</sub>	0,22 $\pm$ 0,09	0,21 $\pm$ 0,06	0,18 $\pm$ 0,06
Vol II / V <sub>T</sub>	0,35 $\pm$ 0,05	0,28 $\pm$ 0,05 *	0,26 $\pm$ 0,05 †
Vol III / V <sub>T</sub>	0,45 $\pm$ 0,08	0,51 $\pm$ 0,1 *	0,57 $\pm$ 0,09 ‡†
Slope II (%/L)	46 $\pm$ 7,7	56 $\pm$ 10 *	63 $\pm$ 11 ‡†
Slope III/N (L <sup>-1</sup> )	0,21 $\pm$ 0,11	0,18 $\pm$ 0,10 *	0,13 $\pm$ 0,07 ‡†
Angle II / III (°)	127 $\pm$ 2,1	125 $\pm$ 7,7	113 $\pm$ 4 ‡†

Lung recruitment increased mean tracing values related to lung efficiency and decreased mean tracing values related to inefficiency. PEEP did not have same effect on dead space. Phase II slopes showed a significant increase with PEEP and ARS although lung recruitment showed the highest values. These steeper slopes were associated with a corresponding decrease in Vol II/VT.

Normalized phase III slope decreased with PEEP ventilation and showed an additional diminution after ARS. Volume of phase III increased with ARS and PEEP compared with ZEEP. The angle between II-III showed significant differences only after the recruitment maneuver.

The following table shows partial pressures of CO<sub>2</sub> and the alveolar ventilation at constant minute ventilation.

Variable	ZEEP	PEEP	ARS
PaCO <sub>2</sub> (kPa)	5,1 ± 0,4	5,2 ± 0,6	4,9 ± 0,5
etCO <sub>2</sub> (kPa)	4,0 ± 0,3	4,0 ± 0,4	3,9 ± 0,2
Pa-etCO <sub>2</sub> (kPa)	1,1 ± 0,5	1,2 ± 0,5	0,9 ± 0,5 *†
VA (l/min)	3,3 ± 0,8	3,4 ± 0,6	3,6 ± 0,8 *†

PaCO<sub>2</sub> = arterial partial pressure of CO<sub>2</sub> (kPa)

etCO<sub>2</sub> = end-tidal partial pressure of CO<sub>2</sub> (kPa)

Pa-etCO<sub>2</sub> = arterial to end-tidal differences of CO<sub>2</sub> (kPa)

VA = alveolar minute ventilation (l/min).

\* ARS against ZEEP, p < 0,05

† ARS against PEEP, p < 0,05.

Pa-etCO<sub>2</sub> was significantly lower and alveolar ventilation larger after ARS compared with ZEEP and PEEP.

Fig. 11 shows measurements of the end-expiratory lung  
5 volume (EELV), the partial paO<sub>2</sub> pressure and the compliance  
at three different ventilation modes. Arterial oxygenation,  
EELV and respiratory compliance showed a significant  
increase after lung recruitment compared with ZEEP and  
PEEP. PEEP without lung recruitment showed compliance  
10 values significantly higher than ZEEP but without changes  
in PaO<sub>2</sub>.

When compared with ZEEP or PEEP, lung recruitment decreased  
those mean tracing values of the CO<sub>2</sub> single breath test  
15 which are related to pulmonary inefficiency and increased  
the ones related to efficiency. The increased efficiency of  
ventilation was associated with an increase in arterial  
oxygenation, expiratory lung volume and respiratory  
compliance, all parameters commonly used as markers of an  
20 open lung condition.

PEEP without recruitment showed an intermediate effect  
between ZEEP and ARS in all mean tracing values studied. In  
anaesthetized patients low levels of PEEP have a  
25 contradictory effect on arterial oxygenation and  
atelectasis. Study results agree in that the recruitment of  
collapsed airways is the main effect of PEEP without a  
recruitment maneuver. Atelectasis treatment requires higher  
airway pressures than the amount of PEEP commonly used  
30 during anesthesia to pop open collapsed alveoli due to the  
incomplete lung recruitment observed with the use of PEEP  
alone.

In contrast to PEEP alone, lung recruitment maneuver  
35 increase both, the cross-sectional area of small airways

and the alveolar-capillary area, by reversing airway and acinar collapse respectively. This total recruitment or open lung condition improves the diffusive  $\text{CO}_2$  transport at the acinar level and could explain the changes observed in the  $\text{CO}_2$  single breath test. Increasing  $\text{CO}_2$  diffusion after the ARS moves the interface between convective-diffusive transport mouthward, thus decreasing the VDAW measured by Fowler's method.

10 Lung recruitment was also associated with an improved efficiency in  $\text{CO}_2$  elimination as expressed by a larger  $\text{VTCO}_{2,\text{br}}$  and a lower  $\text{Pa-etCO}_2$  at constant  $\text{VCO}_2$  and ventilator settings. These results indicate that the area of gas exchange increased and  $\text{V/Q}$  improved.

15 Differences between PEEP and ARS in the distribution of gas volumes within the lung may have an impact on gas exchange and respiratory compliance. Analyzing EELV and the volumes of phase I-II-III, it was observed that the recruitment maneuver re-distributed the VT away from phase I-II towards the volume of phase III (alveolar gas). Compared with ZEEP, PEEP without a recruitment maneuver increased volume of phase III but at the same time, retained some volume within the inefficient parts of the VT (phase I and II).

25 Changes in the slope of phase II and III at ZEEP could be explained by the co-existence of acini with different time constants due to aging and partial collapse.

30 Total lung recruitment has a positive effect on  $\text{CO}_2$  diffusion as reflected by the changes observed in volumes and slopes of phase II-III after ARS. On the one hand it is assumed that an increase in the cross-sectional area caused by airway recruitment could improve the  $\text{CO}_2$  diffusive transport from alveoli to bronchioli. On the other hand, an

35

increase in the area of gas exchange due to a recruitment of atelectasis improved the diffusive transport from the capillaries to the alveoli.

5 In summary, the alveolar recruitment strategy improved the efficiency of ventilation in anesthetized patients. Differences observed in the CO<sub>2</sub> single breath test between PEEP with and without an lung recruitment maneuver can be explained by the effectiveness of the treatment of  
10 pulmonary collapse.

Fig. 12 shows an apparatus according to the invention connected in series with the ventilator to the patient. The apparatus comprises a carbon dioxide sensor for measuring  
15 the expired CO<sub>2</sub> concentration, a pneumotachograph for measuring airway flow, a pressure sensor for measuring airway pressures, and a data processor which determines during a change of the airway pressure from the resulting course of at least one mean tracing value the airway  
20 pressure level at which alveolar opening or lung overdistension or lung open condition or alveolar closing occurs. As indicated in Fig. 12, a feedback line can be included connecting the apparatus with the ventilator thus creating effectively a closed loop system. This allows to  
25 directly control the ventilator, once the optimal values for PIP and PEEP have been identified.

As an example, with regard to the above-mentioned mean tracing values the following logic can be implemented in  
30 the data processor:

#### Detection of lung recruitment

The peak inspiratory pressure is increased continuously and a lung opening is detected, if the slope of phase III reaches a maximal decrease.

- 5 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the intercept of the slope of phase III reaches a maximal increase.

- 10 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the slope of phase II reaches a maximal increase.

- 15 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the intercept of slope of phase II reaches a maximal decrease.

- 20 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the angle II-III reaches a maximal decrease.

- The peak inspiratory pressure is increased continuously and a lung opening is detected, if the volume of phase I reaches a maximal increase.

- 25 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the volume of phase II reaches a maximal increase.

- 30 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the volume of phase III reaches a maximal decrease.

- 35 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the  $VT_{CO_2,br}$  reaches a maximal increase.

The peak inspiratory pressure is increased continuously and a lung opening is detected, if the  $VCO_2$  reaches a maximal increase.

5

The peak inspiratory pressure is increased continuously and a lung opening is detected, if the  $VD_{bohr}$  reaches a maximal decrease.

- 10 The peak inspiratory pressure is increased continuously and a lung opening is detected, if the negative gradient of the resulting course of the measured  $etCO_2$  minus the mean alveolar partial pressure of  $CO_2$  ( $P_{et}-AECO_2$ ) reaches the maximal decrease.

15

#### Detection of lung overdistension

- The peak inspiratory pressure is increased continuously and a lung overdistension is detected, if the  $VD_{aw}$  reaches a  
20 maximal increase, provided the maximal peak inspiratory pressure is below a preset maximal peak inspiratory pressure defined by the user and above a preset minimal peak inspiratory pressure defined by the user.

- 25 The peak inspiratory pressure is increased continuously and a lung overdistension is detected, if the  $VD_{aw}/VT$  reaches a maximal increase, provided the maximal peak inspiratory pressure is below a preset maximal peak inspiratory pressure defined by the user and above a preset minimal  
30 peak inspiratory pressure defined by the user.

- The peak inspiratory pressure is increased continuously and a lung overdistension is detected, if the  $VT_{CO_2,br}$  results in a decrease of about 10% from its previous value,  
35 provided the maximal peak inspiratory pressure is below a

preset maximal peak inspiratory pressure defined by the user and above a preset minimal peak inspiratory pressure defined by the user.

- 5 The peak inspiratory pressure is increased continuously and a lung overdistension is detected, if the VCO<sub>2</sub> results in a decrease of about 10% from its previous value, provided the maximal peak inspiratory pressure is below a preset maximal peak inspiratory pressure defined by the user and above a  
10 preset minimal peak inspiratory pressure defined by the user.

The peak inspiratory pressure is increased continuously and a lung overdistension is detected, if the PAECO<sub>2</sub> results in  
15 a decrease of about 10% from its previous value, provided the maximal peak inspiratory pressure is below a preset maximal peak inspiratory pressure defined by the user and above a preset minimal peak inspiratory pressure defined by the user.

- 20 The peak inspiratory pressure is increased continuously and a lung overdistension is detected, if the angle II-III results in a decrease of about 10% from its previous value, provided the maximal peak inspiratory pressure is below a  
25 preset maximal peak inspiratory pressure defined by the user and above a preset minimal peak inspiratory pressure defined by the user.

The peak inspiratory pressure is increased continuously and  
30 a lung overdistension is detected, if the phase II slope results in a decrease of about 10% from its previous value, provided the maximal peak inspiratory pressure is below a preset maximal peak inspiratory pressure defined by the user and above a preset minimal peak inspiratory pressure  
35 defined by the user.

Detection of open-lung condition

The positive end expiratory pressure is decreased  
5 continuously and an open-lung condition is detected, if the  
VDaw resulting in a minimal value observed before the  
closing pressure is detected.

The positive end expiratory pressure is decreased  
10 continuously and an open-lung condition is detected, if the  
VDaw/VT resulting in a minimal value observed before the  
closing pressure is detected.

The positive end expiratory pressure is decreased  
15 continuously and an open-lung condition is detected, if the  
VTCO<sub>2</sub>,br resulting in a maximal value observed before the  
closing pressure is detected.

The positive end expiratory pressure is decreased  
20 continuously and an open-lung condition is detected, if the  
angle II-III resulting in a minimal value observed before  
the closing pressure is detected.

The positive end expiratory pressure is decreased  
25 continuously and an open-lung condition is detected, if the  
phase II slope resulting in a maximal value observed before  
the closing pressure is detected.

The positive end expiratory pressure is decreased  
30 continuously and an open-lung condition is detected, if the  
Volume of phase II resulting in a minimal value observed  
before the closing pressure is detected.

The positive end expiratory pressure is decreased  
35 continuously and an open-lung condition is detected, if the

Volume of phase III resulting in a maximal value observed before the closing pressure is detected.

The positive end expiratory pressure is decreased  
5 continuously and an open-lung condition is detected, if the intercept of phase II slope resulting in a maximal value observed before the closing pressure is detected.

#### Detection of lung re-collapse

10

The positive end expiratory pressure is decreased continuously and a closing pressure of the lungs is detected, if the curve of the mean tracing values of the V<sub>Daw</sub> shows a permanent gradient change after the point  
15 corresponding to the open-lung condition values, provided the closing pressure is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

20

The positive end expiratory pressure is decreased continuously and a closing pressure of the lungs is detected, if the curve of the mean tracing values of the V<sub>TCO<sub>2</sub>,br</sub> shows a permanent gradient change after the point  
25 corresponding to the open-lung condition values, provided the closing pressure is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

30

The positive end expiratory pressure is decreased continuously and a closing pressure of the lungs is detected, if the curve of the mean tracing values of the V<sub>CO<sub>2</sub></sub> shows a permanent gradient change after the point  
35 corresponding to the open-lung condition values, provided

the closing pressure is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

5

The positive end expiratory pressure is decreased continuously and a closing pressure of the lungs is detected, if the curve of the mean tracing values of the volume of phase II shows a permanent gradient change after  
10 the point corresponding to the open-lung condition values, provided the closing pressure is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

15

The positive end expiratory pressure is decreased continuously and a closing pressure of the lungs is detected, if the curve of the mean tracing values of the volume of phase III shows a permanent gradient change after  
20 the point corresponding to the open-lung condition values, provided the closing pressure is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

25

The positive end expiratory pressure is decreased continuously and a closing pressure of the lungs is detected, if the curve of the mean tracing values of the angle II-III shows a permanent gradient change after the  
30 point corresponding to the open-lung condition values, provided the closing pressure is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

35

The positive end expiratory pressure is decreased continuously and a closing pressure of the lungs is detected, if the curve of the mean tracing values of the intercept of phase II slope shows a permanent gradient change after the point corresponding to the open-lung condition values, provided the closing pressure is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

10

#### Re-opening procedure

The peak inspiratory pressure is set 2 - 5 cmH<sub>2</sub>O above the value identified during the detection of the open-lung condition, provided this value is below a preset maximum peak inspiratory pressure defined by the user and above a preset minimum peak inspiratory pressure defined by the user.

20 The positive end expiratory pressure is set 2 - 3 cmH<sub>2</sub>O above the value identified during the detection of the lung re-collapse condition, provided this value is below a preset maximum positive end expiratory pressure defined by the user and above a preset minimum positive end expiratory pressure defined by the user.

The peak inspiratory pressure is set to a value to achieve the desired tidal volume, provided this value is below a preset maximum peak inspiratory pressure defined by the user and above a preset minimum peak inspiratory pressure defined by the user.

Fig. 13 shows a plot of the O<sub>2</sub> single breath test depicting the O<sub>2</sub> gas concentration during the patient exhale cycle. Plotted is the expiratory oxygen fraction in percentage

35

against time and a volume rate measurement against time. This plot corresponds to the  $O_2$  single breath test. The plotted exhale cycle can be subdivided into two stages, one representing the airway dead space and the other one  
5 representing the alveolar tidal volume. The expiratory oxygen fraction does not decrease considerably within the first stage, since the gas expired represents gas from the airway conduction structures where gas exchange does not occur. On the other side, the expiratory oxygen fraction is  
10 considerably lower in the second stage, when unmixed gas from regions of the lung which normally are in active exchange with the alveolar tissue is expired. Within Fig. 13  $paO_2$  is the partial pressure of oxygen and  $etO_2$  is the endtidal oxygen concentration of a single breath.

15 The plot according to Fig. 13 is formed by the exhaled partial pressure of  $O_2$  against the expiratory tidal volume. Its analysis can be performed, e.g., using a fast side-stream or main-stream oxygen sensor. Furthermore, a  
20 computer is provided to record and analyze data.

The side-stream  $O_2$  signal has a time delay with respect to the flow signal. A corresponding software can correct the  $O_2$  delays automatically using mathematical algorithms. The  
25  $VTO_{2,br}$  or area under the curve can be computed by integrating expired flow and  $O_2$  in each breath. Analysis of dead space can be done on-line and/or off-line using Fowler's analysis and adding arterial  $PO_2$  values to the  $O_2$  curve of the single breath test.

30 Fig. 14 shows a plot comparing the  $CO_2$  gas concentration during a  $CO_2$  single breath test with the  $O_2$  gas concentration during an  $O_2$  single breath test during the patient exhale cycle. As can be clearly seen, the curve of  
35 the  $O_2$  single breath test looks like a mirror image of the

curve of the CO<sub>2</sub> single breath test. Whereas, in this example simultaneous measurements of the CO<sub>2</sub> gas concentration and the O<sub>2</sub> gas concentration during a single breath test were performed, usually it is sufficient to perform measurements of only one gas concentration to determine the status of the lung according to the invention.

Fig. 15 shows some possible mean tracing values within a plot of an O<sub>2</sub> single breath test. As already mentioned, principally any gas concentration can be used within the method and apparatus according to the invention, provided this gas concentration allows to determine the status of the lung in accordance with the invention. In addition to the example given so far, namely to utilize the CO<sub>2</sub> concentration, Fig. 15 demonstrates that the O<sub>2</sub> concentration can be used equally well.

In order to determine the required mean tracing values, the curve shown in Fig. 15 is divided into three phases. Phase I represents CO<sub>2</sub> free gas expired from the airway conduction structures where gas exchange does not occur. Hence, the O<sub>2</sub> concentration is highest and remains comparatively constant. Phase II is characterized by an counter-S-shaped downswing and represents the transition from airway to alveolar gas. Phase III reflects the exhalation of unmixed gas from regions of the lung which normally are in active exchange with the alveolar tissue and thus closely resembles at least in healthy patients gas properties associated with arterial blood in contact with the lung for gas exchange, i.e. CO<sub>2</sub> release and O<sub>2</sub> absorption. In normal lungs, Phase III is characterized by a horizontal level since ventilated and perfused alveolar regions are closely matched. In a diseased lung, Phase III

may not appear horizontal due to a mismatch in ventilation and perfusion of this lung region.

Fig. 15 shows only two possible mean tracing values within a plot of the O<sub>2</sub> single breath test, which are

slope II or steepest mean slope	determined by the steepest mean slope (either over time or over volume) of the O <sub>2</sub> concentration in the expired gas in vicinity of the point of inflection, and
slope III or endtidal mean slope	determined by the mean slope (either over time or over volume) of the O <sub>2</sub> concentration in the expired gas towards the final stage of a single breath.

However, the same types of mean tracing values as obtained from a CO<sub>2</sub> single breath test can be determined from Fig. 15. The two presented mean tracing values can be obtained in the same way as described for the CO<sub>2</sub> single breath test with reference to Fig. 6.

It should be noted with reference to Fig. 14, that certain mean tracing values will have opposite signs when performing an O<sub>2</sub> single breath test compared to corresponding values obtained from a CO<sub>2</sub> single breath test.

According to the invention, a gas concentration can be used to determine the status of the lung, i.e. the O<sub>2</sub> gas concentration or the CO<sub>2</sub> gas concentration. However, the results of the evaluation of an O<sub>2</sub> single breath test according to Fig. 15 could be combined with the results of an evaluation of a CO<sub>2</sub> single breath test. This would increase the accuracy of the diagnostic method considerably.

## ABBREVIATIONS

	ARS	alveolar recruitment strategy
5	BTPS	ambient pressure and water vapor saturation
	DLT	double lumen tube
	EELV	end-expiratory lung volume
	etCO <sub>2</sub>	endtidal CO <sub>2</sub> concentration
	FaeCO <sub>2</sub>	mean expired alveolar fraction of CO <sub>2</sub>
10	FiO <sub>2</sub>	inspired oxygen fraction
	FIR	finite impulse response
	OLV	one-lung ventilation
	paCO <sub>2</sub>	partial pressure of CO <sub>2</sub>
	paeCO <sub>2</sub>	mean alveolar fraction of CO <sub>2</sub>
15	paO <sub>2</sub>	partial pressures of oxygen
	PEEP	positive end-expiratory pressure
	PIP	peak inspiratory pressure
	RQ	respiratory quotient
	RR	respiratory rate
20	slope II	steepest mean slope
	slope III	endtidal mean slope
	SO <sub>2</sub>	hemoglobin oxygen saturation
	TLV	intermittent ventilation
	V/Q	ventilation/perfusion relationship
25	VCO <sub>2</sub>	carbon dioxide elimination
	VD <sup>alv</sup>	alveolar dead space
	VD <sup>aw</sup>	airway dead space
	VD <sup>phy</sup>	physiological dead space
	VO <sub>2</sub>	oxygen consumption
30	VT	tidal volume
	VT <sup>alv</sup>	alveolar tidal volume
	VT <sub>CO<sub>2</sub>,br</sub>	expired volume of CO <sub>2</sub> per breath
	VTe	expired tidal volume
	ZEEP	positive end-expiratory pressure

**Claims**

1. Method for determining the status of a lung ventilated by an artificial ventilator, comprising the steps of:
  - a) obtaining data samples of a gas concentration of the expired gas over a single breath,
  - b) selecting a plurality of data samples from said obtained data samples,
  - c) calculating a mean tracing value being sensitive to changes of alveolar dead space on the basis of said selected data samples,
  - d) repeating steps a), b) and c) for obtaining a plurality of mean tracing values, and
  - e) changing the peak inspiratory pressure and the positive end expiratory pressure of the artificial ventilator, wherein from the observation of the resulting course of the plurality of calculated mean tracing values the peak inspiratory pressure at which alveolar opening or lung overdistension and/or the positive end expiratory pressure at which lung open condition or alveolar closing occurs are detected.
2. Method according to claim 1, wherein the gas concentration represents the CO<sub>2</sub> concentration.
3. Method according to claim 2, wherein the data samples according to step a) are obtained in the time domain.

4. Method according to claim 3, wherein the obtained data samples are converted from the time domain into the volumetric domain.
5. Method according to one of the claims 2 - 4, wherein a first mean tracing value is represented by the endtidal mean slope of the CO<sub>2</sub> concentration in the expired gas during a single breath.
6. Method according to claim 5, wherein starting from alveolar closing the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath and wherein an alveolar opening of the lung is detected, if the resulting course of the plurality of determined first mean tracing values reaches a minimum.
7. Method according to one of the claims 5 - 6, wherein starting from alveolar opening the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath and wherein a lung overdistension is detected, if the positive gradient of the resulting course of the plurality of determined first mean tracing values reaches a maximum.
8. Method according to one of the claims 5 - 7, wherein starting from lung overdistension the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath and wherein an open lung condition is detected, if the resulting course of the plurality of determined first mean tracing values reaches a minimum.
9. Method according to one of the claims 5 - 8, wherein starting from an open lung condition the positive end expiratory pressure of the artificial ventilator is

decreased stepwise breath by breath and wherein an alveolar closing is detected, if the positive gradient of the resulting course of the plurality of determined first mean tracing values reaches a maximum.

5

10. Method according to one of the claims 2 - 9, wherein a second mean tracing value is represented by the steepest mean slope of the CO<sub>2</sub> concentration in the expired gas during a single breath.

10

11. Method according to claim 10, wherein starting from alveolar closing the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath and wherein an alveolar opening of the lung is detected, if the resulting course of the plurality of determined second mean tracing values reaches a maximum.

15

12. Method according to one of the claims 10 - 11, wherein starting from alveolar opening the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath and wherein a lung overdistension is detected, if the negative gradient of the resulting course of the plurality of determined second mean tracing values reaches a minimum.

20

25

13. Method according to one of the claims 10 - 12, wherein starting from lung overdistension the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath and wherein an open lung condition is detected, if the resulting course of the plurality of determined second mean tracing values reaches a maximum.

30

14. Method according to one of the claims 10 - 13, wherein starting from an open lung condition the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath and wherein an  
5 alveolar closing is detected, if the negative gradient of the resulting course of the plurality of determined second mean tracing values reaches a minimum.
15. Method according to one of the claims 2 - 14, wherein a  
10 third mean tracing value is represented by the angle between the endtidal mean slope and the steepest mean slope of the CO<sub>2</sub> concentration in the expired gas during a single breath.
- 15 16. Method according to claim 15, wherein starting from alveolar closing the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath and wherein an alveolar opening of the lung is detected, if the resulting course of the plurality of  
20 determined third mean tracing values reaches a minimum.
17. Method according to one of the claims 15 - 16, wherein starting from alveolar opening the peak inspiratory pressure of the artificial ventilator is increased  
25 stepwise breath by breath and wherein a lung overdistension is detected, if the positive gradient of the resulting course of the plurality of determined third mean tracing values reaches a maximum.
- 30 18. Method according to one of the claims 15 - 17, wherein starting from lung overdistension the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath and wherein an open lung condition is detected, if the resulting course of

the plurality of determined third mean tracing values reaches a minimum.

19. Method according to one of the claims 15 - 18, wherein  
5 starting from an open lung condition the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath and wherein an alveolar closing is detected, if the positive gradient of the resulting course of the plurality of determined  
10 third mean tracing values reaches a maximum.

20. Method according to one of the claims 2 - 19, wherein a plurality of different types of mean tracing values are calculated in parallel and wherein from the resulting  
15 course of the plurality of different types of mean tracing values the peak inspiratory pressure at which alveolar opening or lung overdistension and/or the positive end expiratory pressure at which lung open condition or alveolar closing occurs are detected.

20  
21. Method according to one of the claims 2 - 20, wherein during a recruitment maneuver of the lung the peak inspiratory pressure is set above the peak inspiratory pressure at which alveolar opening has been detected  
25 and the positive end-expiratory pressure is set above the positive end expiratory pressure at which alveolar closing has been detected.

22. Apparatus for determining the status of a lung  
30 ventilated by an artificial ventilator, comprising:

a sensor for measuring a gas concentration in the expired gas during a single breath,

an analog to digital converter for obtaining data samples of said gas concentration of the expired gas over a single breath in the time domain,

5 means for selecting a plurality of data samples from said obtained data samples,

means for calculating a mean tracing value being sensitive to changes of alveolar dead space on the  
10 basis of said selected data samples, and

a data processor which detects during a change of the airway pressure of the artificial ventilator from the resulting course of a plurality of calculated mean  
15 tracing values the peak inspiratory pressure at which alveolar opening or lung overdistension occurs and/or the positive end expiratory pressure at which lung open condition or alveolar closing occurs.

20 23. Apparatus according to claim 22, wherein the gas concentration represents the CO<sub>2</sub> concentration.

24. Apparatus according to claim 23, wherein the analog to digital converter converts the data samples in the time  
25 domain.

25. Apparatus according to claim 23, further comprising a means for assessing a volumetric rate of the expired gas and a means for converting the obtained data  
30 samples from the time domain to the volumetric domain.

26. Apparatus according to one of the claims 23 - 25, wherein a first mean tracing value is represented by the endtidal mean slope of the CO<sub>2</sub> concentration in the  
35 expired gas during a single breath.

27. Apparatus according to claim 26, wherein starting from alveolar closing the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath and wherein an alveolar opening of the lung is detected, if the resulting course of the plurality of determined first mean tracing values reaches a minimum.
28. Apparatus according to one of the claims 26 - 27, wherein starting from alveolar opening the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath and wherein a lung overdistension is detected, if the positive gradient of the resulting course of the plurality of determined first mean tracing values reaches a maximum.
29. Apparatus according to one of the claims 26 - 28, wherein starting from lung overdistension the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath and wherein an open lung condition is detected, if the resulting course of the plurality of determined first mean tracing values reaches a minimum.
30. Apparatus according to one of the claims 26 - 29, wherein starting from an open lung condition the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath and wherein an alveolar closing is detected, if the positive gradient of the resulting course of the plurality of determined first mean tracing values reaches a maximum.
31. Apparatus according to one of the claims 23 - 30, wherein a second mean tracing value is represented by

the steepest mean slope of the CO<sub>2</sub> concentration in the expired gas during a single breath.

32. Apparatus according to claim 31, wherein starting from  
5 alveolar closing the peak inspiratory pressure of the artificial ventilator is increased stepwise breath by breath and wherein an alveolar opening of the lung is detected, if the resulting course of the plurality of determined second mean tracing values reaches a  
10 maximum.
33. Apparatus according to one of the claims 31 - 32, wherein starting from alveolar opening the peak inspiratory pressure of the artificial ventilator is  
15 increased stepwise breath by breath and wherein a lung overdistension is detected, if the negative gradient of the resulting course of the plurality of determined second mean tracing values reaches a minimum.
- 20 34. Apparatus according to one of the claims 31 - 33, wherein starting from lung overdistension the positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath and wherein an open lung condition is detected, if the resulting course of  
25 the plurality of determined second mean tracing values reaches a maximum.
35. Apparatus according to one of the claims 31 - 34, wherein starting from an open lung condition the  
30 positive end expiratory pressure of the artificial ventilator is decreased stepwise breath by breath and wherein an alveolar closing is detected, if the negative gradient of the resulting course of the plurality of determined second mean tracing values  
35 reaches a minimum.

36. Apparatus according to one of the claims 23 - 35,  
wherein a third mean tracing value is represented by  
the angle between the endtidal mean slope and the  
5 steepest mean slope of the CO<sub>2</sub> concentration in the  
expired gas during a single breath.
37. Apparatus according to claim 36, wherein starting from  
alveolar closing the peak inspiratory pressure of the  
10 artificial ventilator is increased stepwise breath by  
breath and wherein an alveolar opening of the lung is  
detected, if the resulting course of the plurality of  
determined third mean tracing values reaches a minimum.
- 15 38. Apparatus according to one of the claims 35 - 37,  
wherein starting from alveolar opening the peak  
inspiratory pressure of the artificial ventilator is  
increased stepwise breath by breath and wherein a lung  
overdistension is detected, if the positive gradient of  
20 the resulting course of the plurality of determined  
third mean tracing values reaches a maximum.
39. Apparatus according to one of the claims 36 - 38,  
wherein starting from lung overdistension the positive  
25 end expiratory pressure of the artificial ventilator is  
decreased stepwise breath by breath and wherein an open  
lung condition is detected, if the resulting course of  
the plurality of determined third mean tracing values  
reaches a minimum.
- 30 40. Apparatus according to one of the claims 36 - 39,  
wherein starting from an open lung condition the  
positive end expiratory pressure of the artificial  
ventilator is decreased stepwise breath by breath and  
35 wherein an alveolar closing is detected, if the

positive gradient of the resulting course of the plurality of determined third mean tracing values reaches a maximum.

5 41. Apparatus according to one of the claims 23 - 40,  
wherein a plurality of different types of mean tracing  
values are calculated in parallel and wherein from the  
resulting course of the plurality of different types of  
mean tracing values the peak inspiratory pressure at  
10 which alveolar opening or lung overdistension and/or  
the positive end expiratory pressure at which lung open  
condition or alveolar closing occurs are detected.

42. Apparatus according to one of the claims 23 - 41,  
15 wherein during a recruitment maneuver of the lung the  
peak inspiratory pressure is set above the peak  
inspiratory pressure at which alveolar opening has been  
detected and the positive end-expiratory pressure is  
set above the positive end expiratory pressure at which  
20 alveolar closing has been detected.

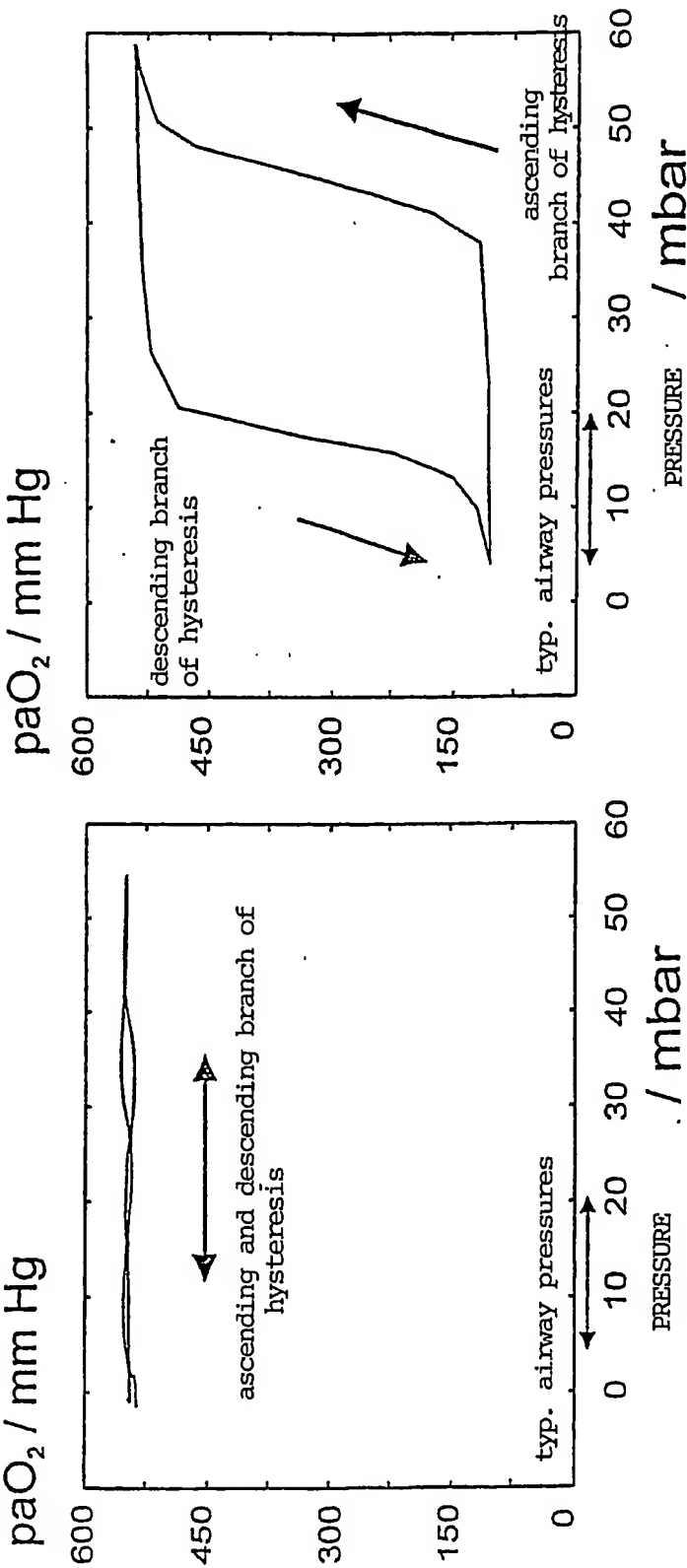


Fig. 1

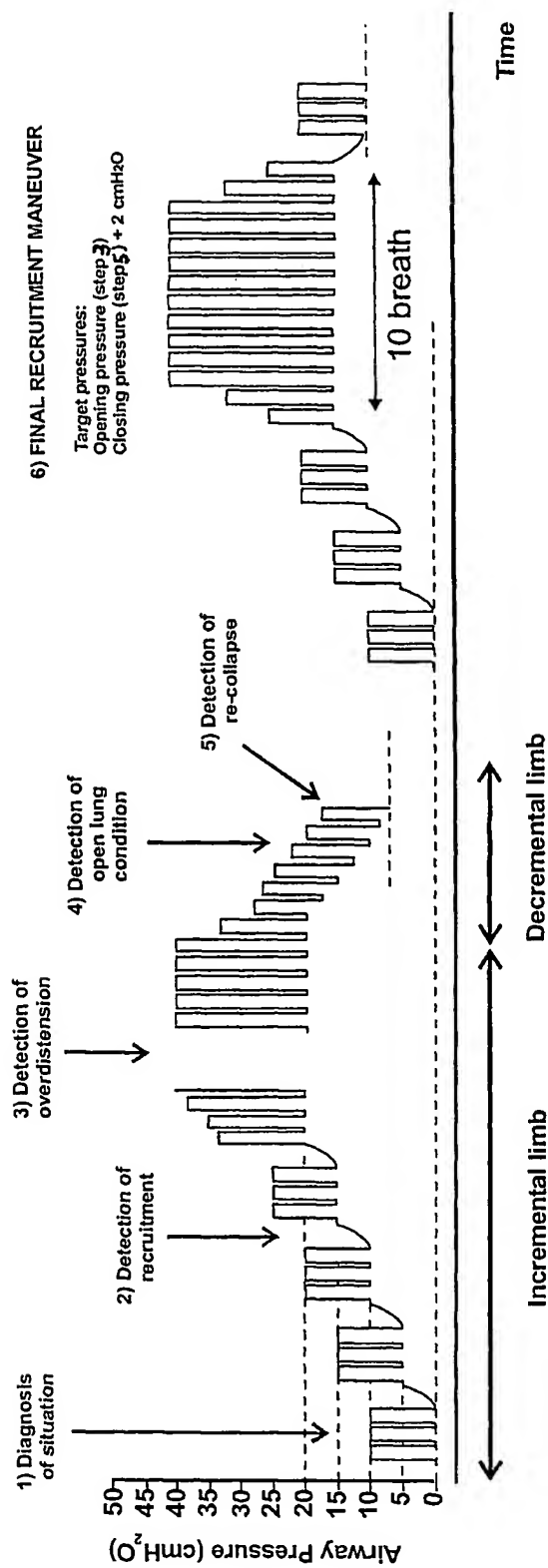


Fig. 2

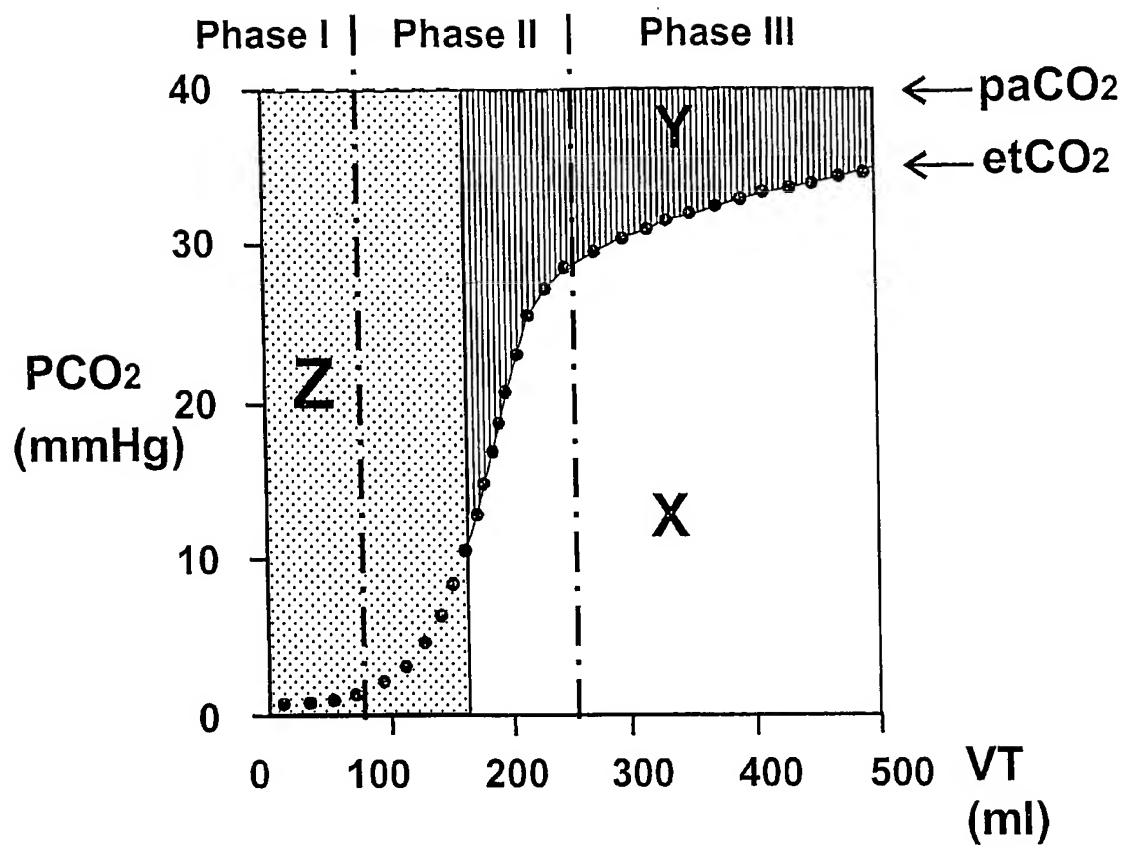


Fig. 3

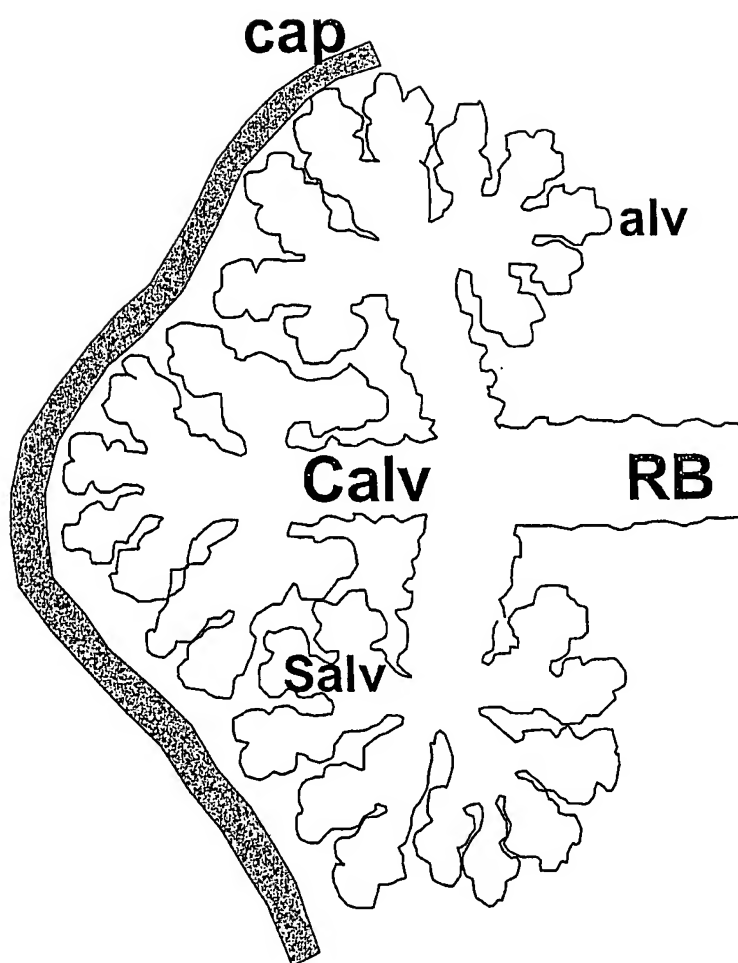


Fig. 4

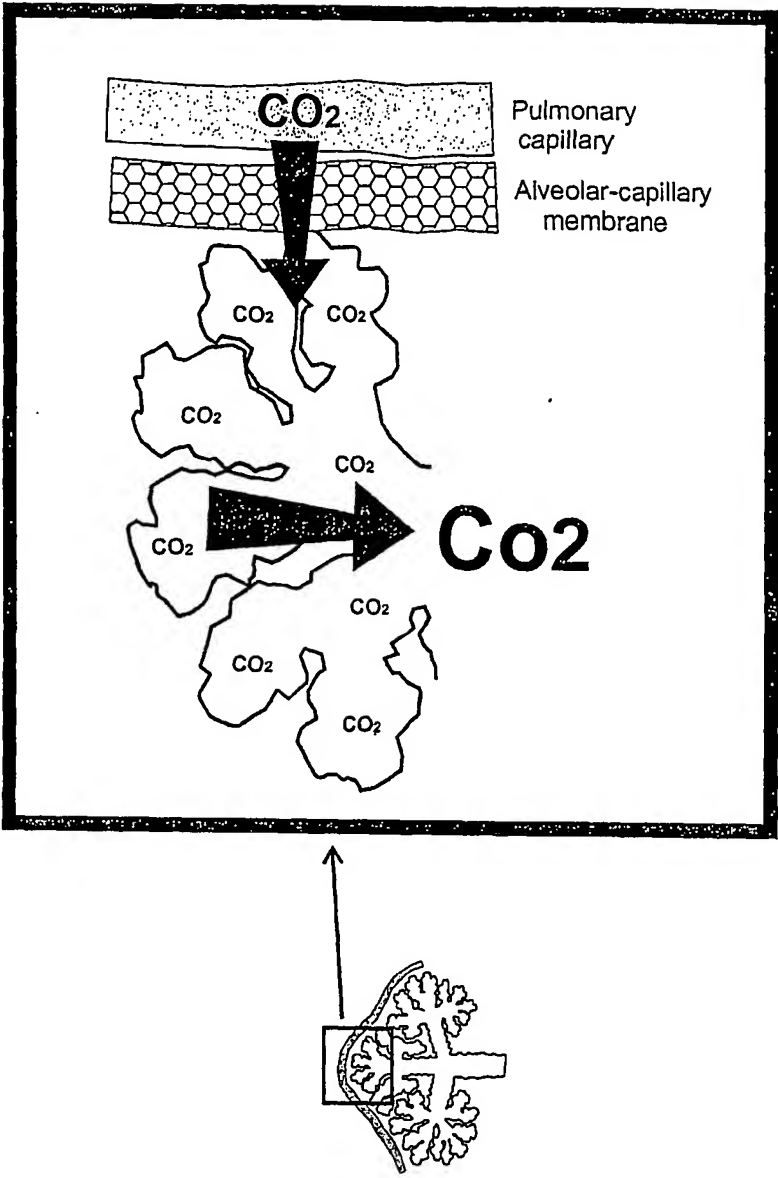


Fig. 5

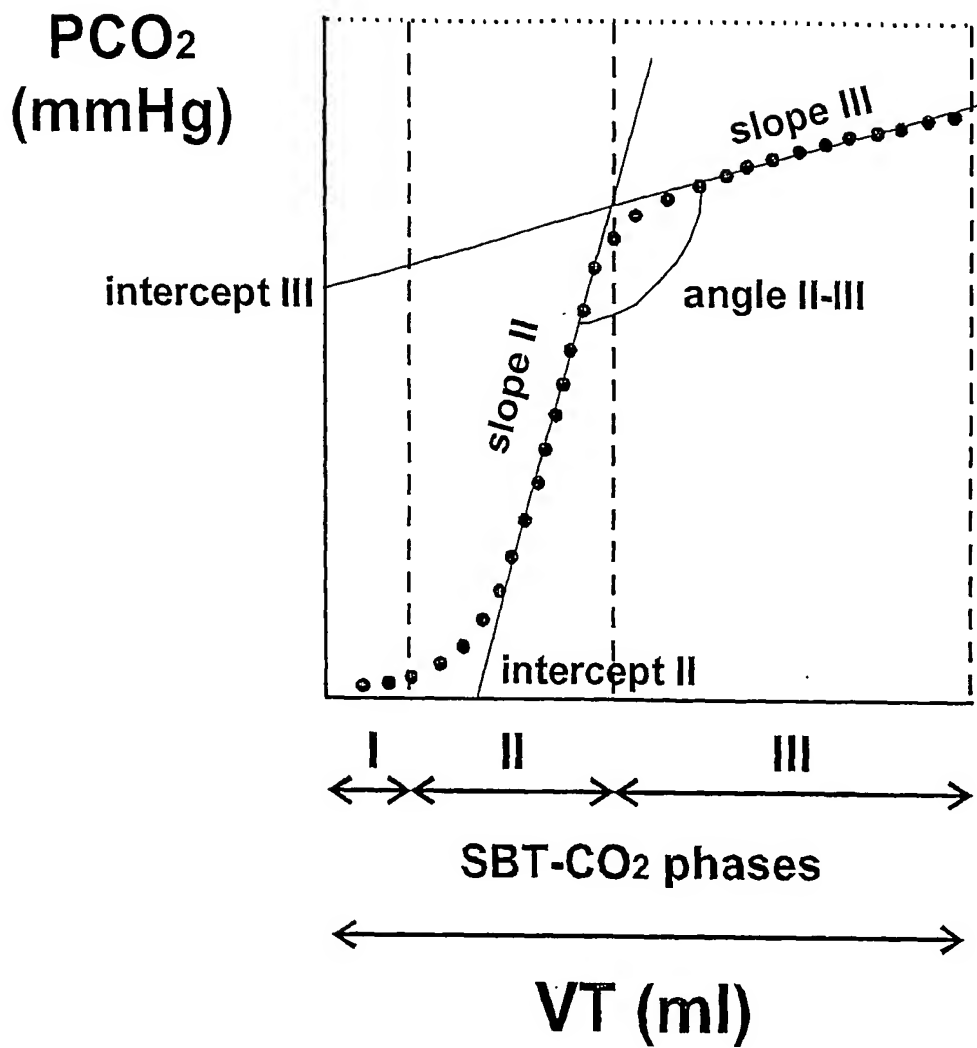


Fig. 6

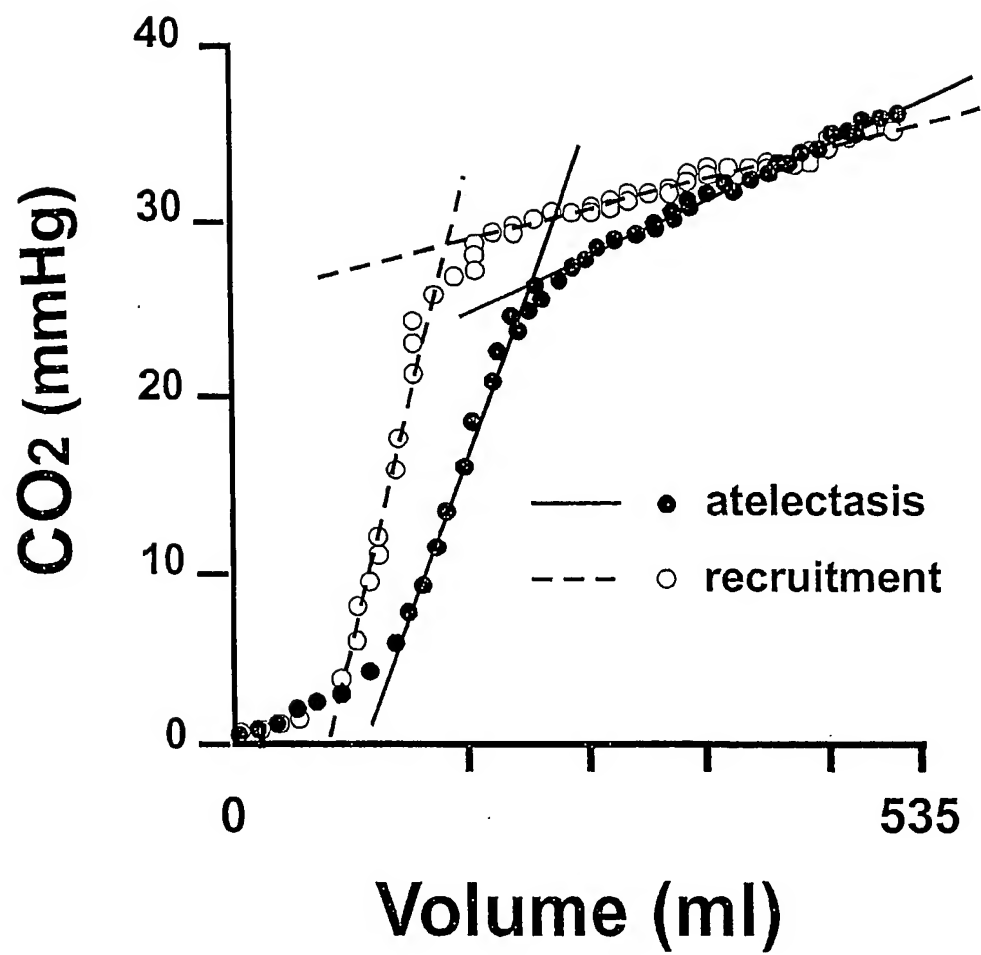


Fig. 7

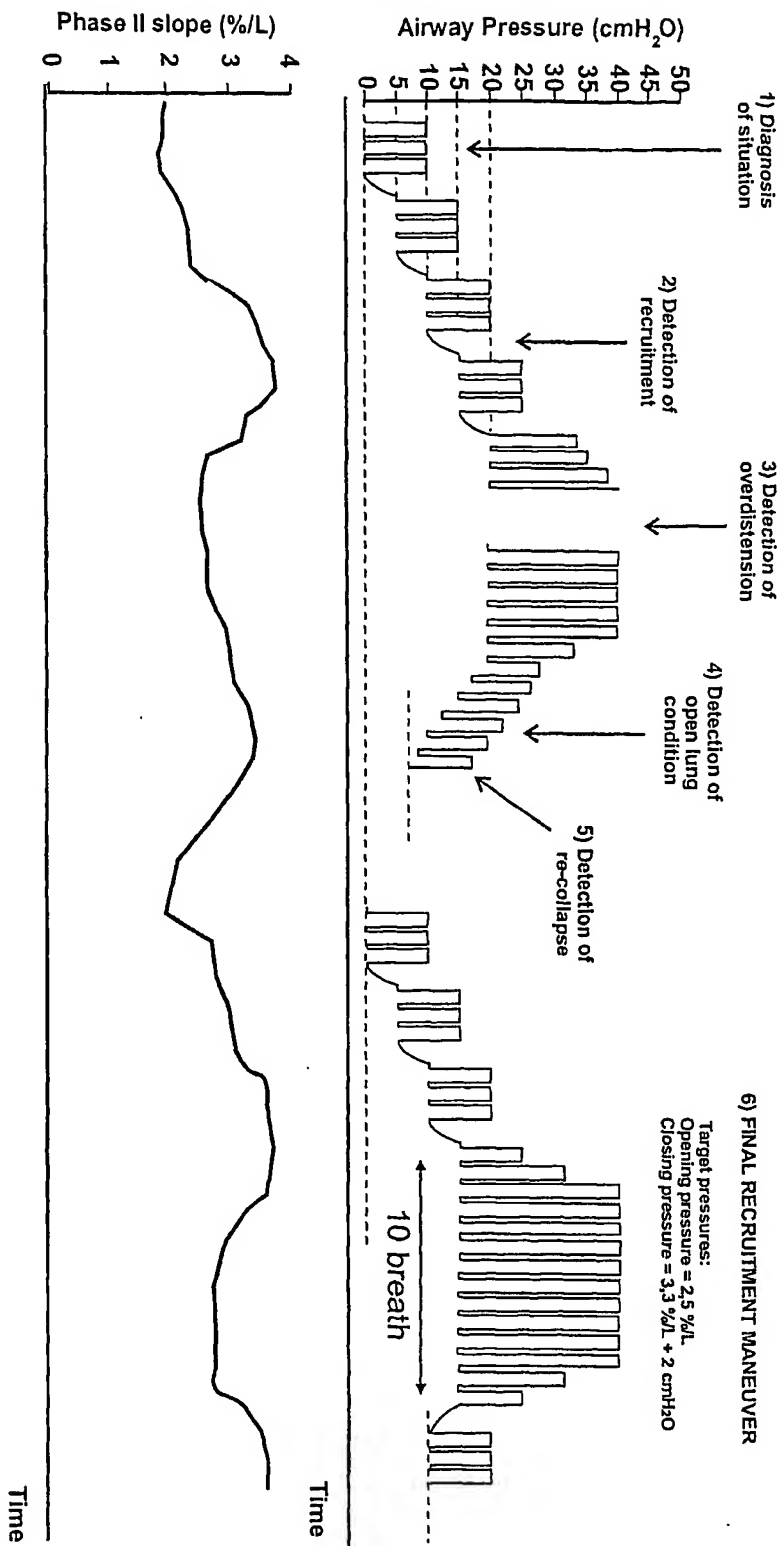


Fig. 8

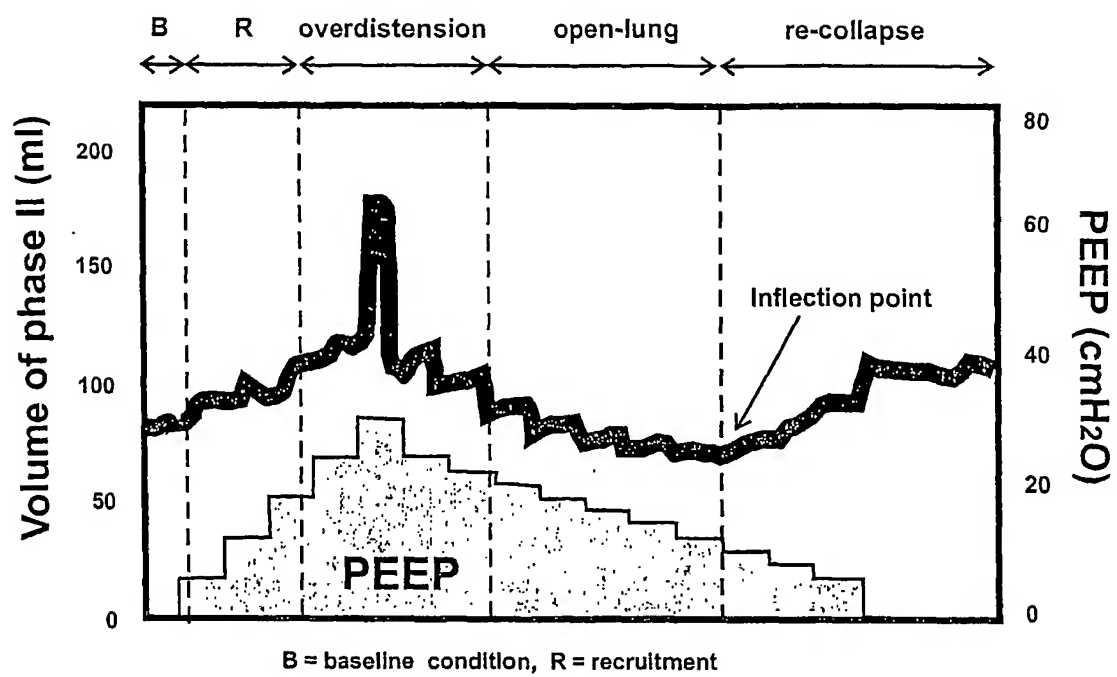


Fig. 9

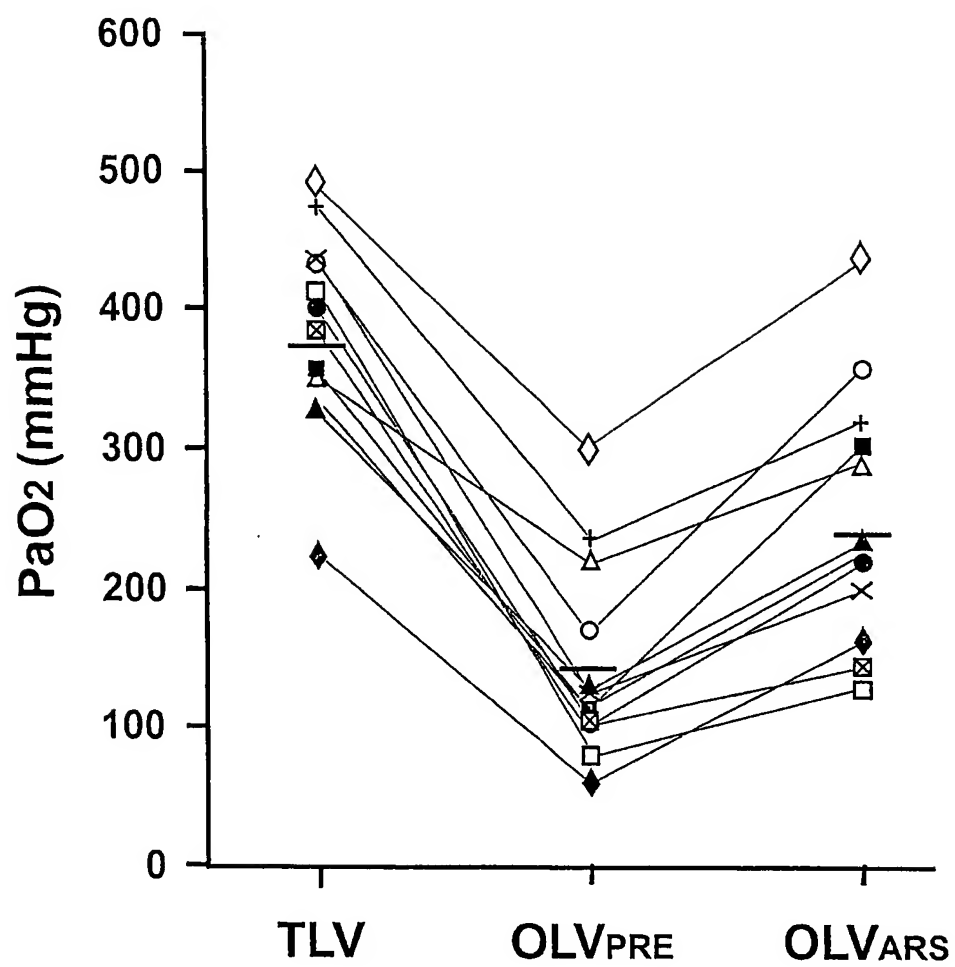


Fig. 10

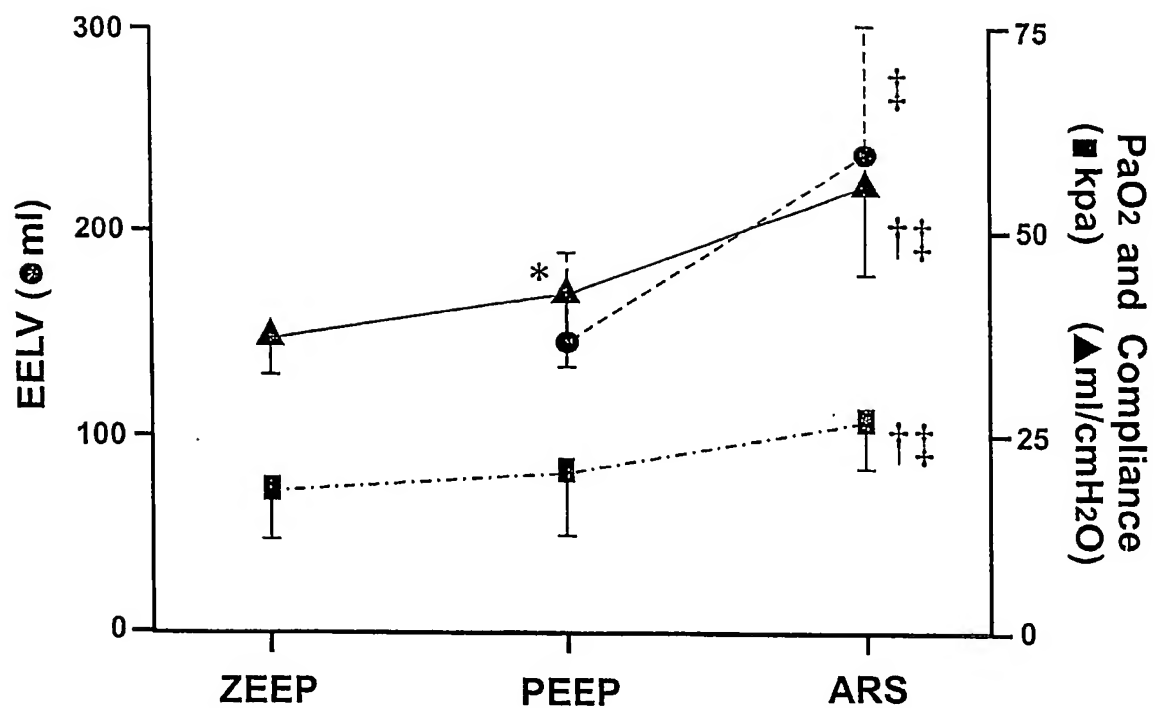
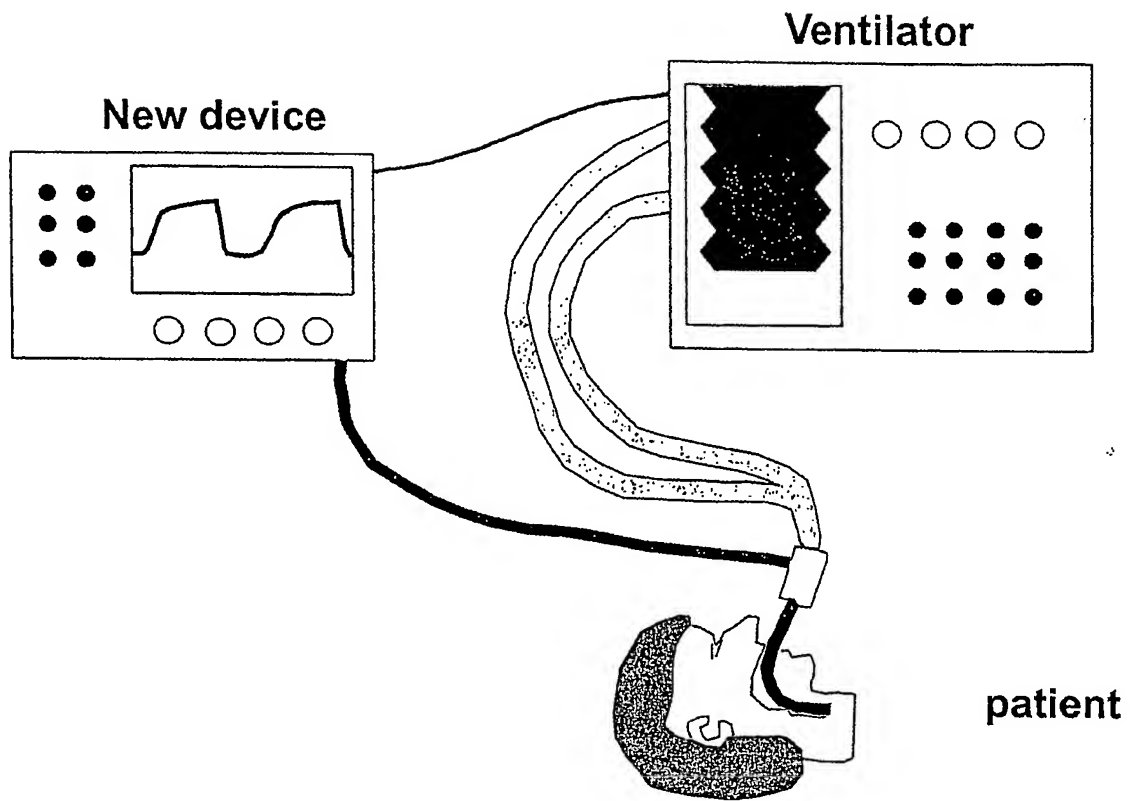


Fig. 11

**Fig. 12**

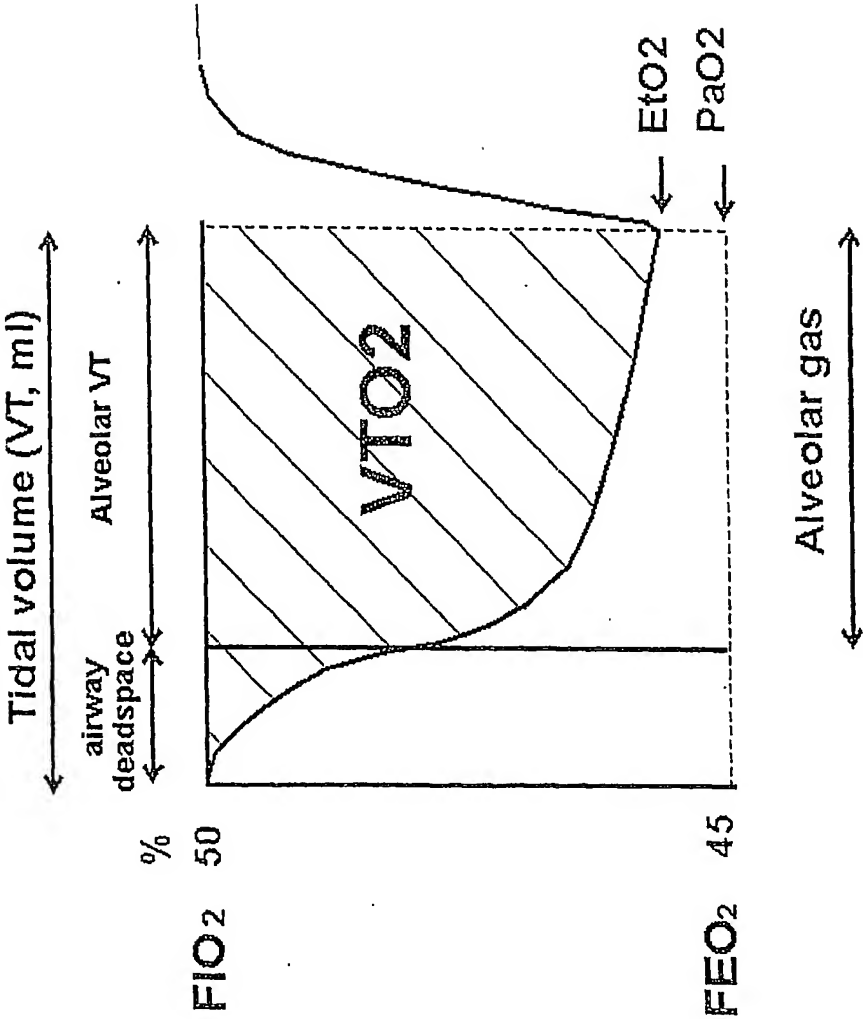
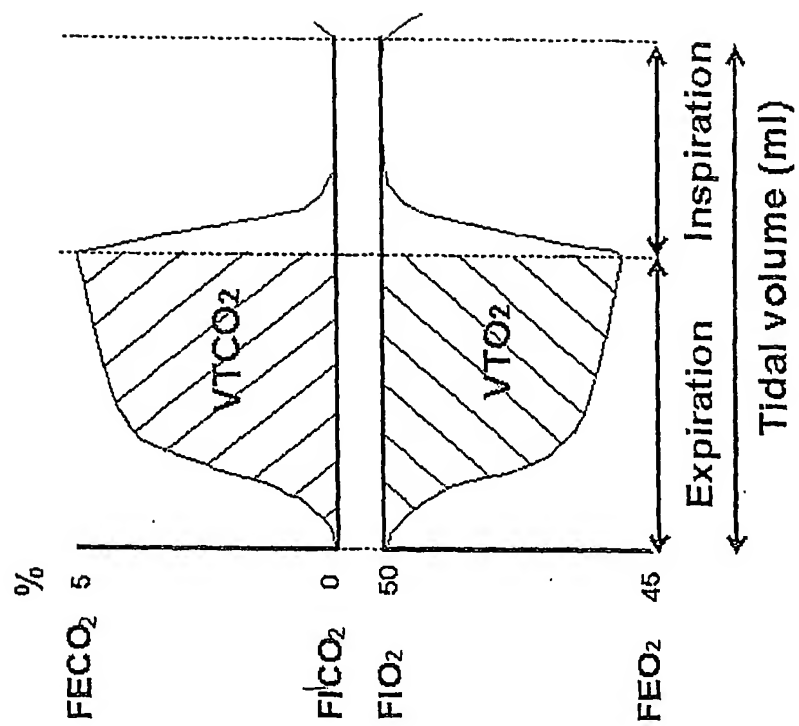


Fig. 13

VOLUMETRIC CAPNOGRAPHY AND OXYGRAPHY**Fig. 14**

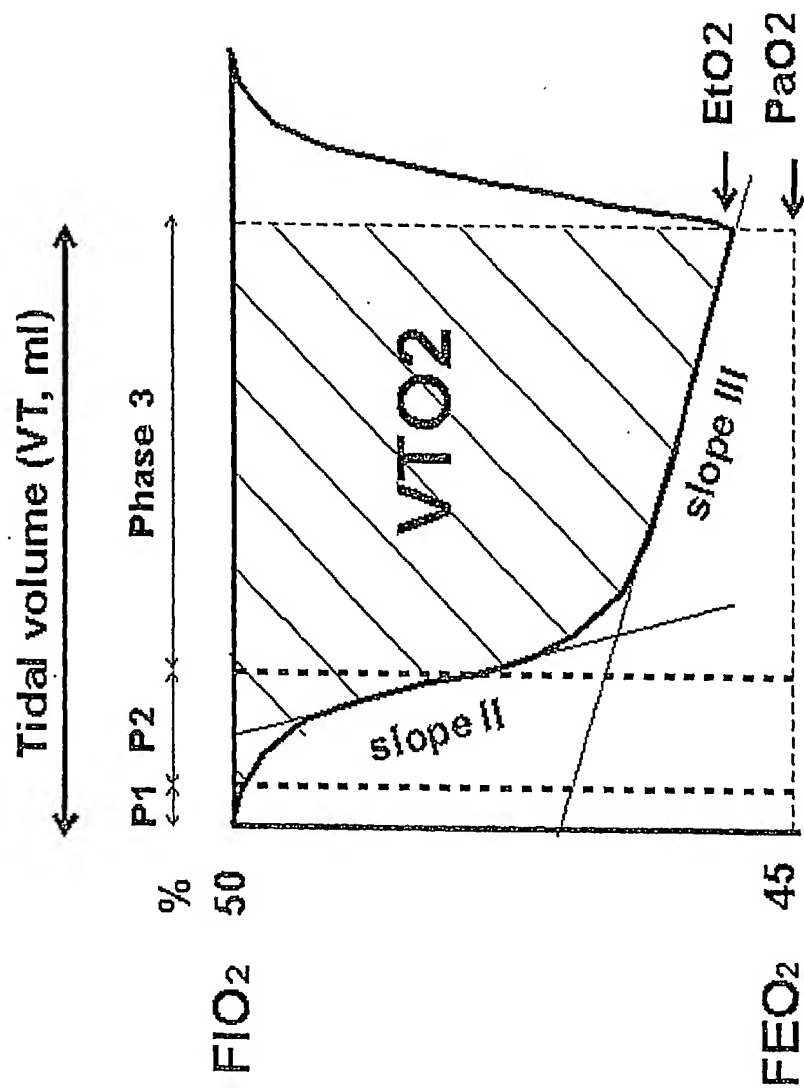


Fig. 15

## INTERNATIONAL SEARCH REPORT

PCT/EP2005/003181

## A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 A61M16/00 A61B5/083

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 A61M A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 00/44427 A (LEONHARDT STEFFEN ; BOEHM STEPHAN (DE)) 3 August 2000 (2000-08-03) cited in the application the whole document	22-42
A	EP 0 745 403 A (LACHMANN BURKHARD) 4 December 1996 (1996-12-04) claim 1	22-42
A	EP 0 745 402 A (LACHMANN BURKHARDT) 4 December 1996 (1996-12-04) abstract	22-42
A	US 6 402 697 B1 (CALKINS JERRY M ET AL) 11 June 2002 (2002-06-11) abstract	22-42
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☒ Further documents are listed in the continuation of box C.☒ Patent family members are listed in annex.

## \* Special categories of cited documents :

\*A\* document defining the general state of the art which is not considered to be of particular relevance

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\*O\* document referring to an oral disclosure, use, exhibition or other means

\*P\* document published prior to the international filing date but later than the priority date claimed

\*T\* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

\*X\* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

\*Y\* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

\*&amp;\* document member of the same patent family

Date of the actual completion of the international search

9 June 2005

Date of mailing of the international search report

16/06/2005

Name and mailing address of the ISA

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## INTERNATIONAL SEARCH REPORT

PCT/EP2005/003181

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 753 320 A (LACHMANN BURKHARDT) 15 January 1997 (1997-01-15) abstract -----	22-42
A	WO 96/24285 A (RAYBURN DANIEL B) 15 August 1996 (1996-08-15) cited in the application abstract -----	
A	WO 92/04865 A (UNIV MELBOURNE) 2 April 1992 (1992-04-02) cited in the application abstract -----	

# INTERNATIONAL SEARCH REPORT

PCT/EP2005/003181

## Box II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☒ Claims Nos.: 1-21  
because they relate to subject matter not required to be searched by this Authority, namely:  
Rule 39.1(iv) PCT - Method for treatment of the human or animal body by therapy
2. ☐ Claims Nos.:  
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
3. ☐ Claims Nos.:  
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

## Box III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
- ☐ No protest accompanied the payment of additional search fees.

## INTERNATIONAL SEARCH REPORT

PCT/EP2005/003181

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